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Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall

Michael A. Taylor
Department of Physics, University of the West Indies, Mona, Jamaica

David B. Enfield
Physical Oceanography Division, NOAA/AOML, Miami, Florida, USA

A. Anthony Chen
Department of Physics, University of the West Indies, Mona, Jamaica

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[1] The Caribbean rainfall season runs from May through November and is distinctly bimodal in nature. The bimodality allows for a convenient division into an early season (May–June–July) and a late season (August–September–October). Evidence suggests that interannual variability in the early season is influenced strongly by anomalies in the sea surface temperatures of the tropical North Atlantic, with positive anomalies over a narrow latitudinal band (0°–20°N) being associated with enhanced Caribbean rainfall. The coincidence of this band with the main development region for tropical waves suggests a modification of the development of the waves by the warmer tropical Atlantic. The strong influence of the tropical North Atlantic wanes in the late season, with the equatorial Pacific and equatorial Atlantic becoming more significant modulators of interannual variability. The spatial pattern of significant correlation suggests strongly the influence of the El Niño/La Niña phenomenon, with a warm Pacific associated with a depressed late season and vice versa. There additionally seems to be a robust relationship between late season Caribbean rainfall and an east-west gradient of sea surface temperature (SST) between the two equatorial oceanic basins. Oppositely signed SST anomalies in the NINO3 region and the central equatorial Atlantic (0°–15°W, 5°S–5°N) are well correlated with Caribbean rainfall for this period. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3319 Meteorology and Atmospheric Dynamics: General circulation; 4215 Oceanography: General: Climate and interannual variability (3309); *KEYWORDS:* Caribbean, rainfall, El Niño, tropical Atlantic, warm pool, model

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1. Introduction

[2] The Caribbean rainfall season spans May through November, and is distinctly bimodal in nature (Figure 1). A brief dryer period in July allows for a convenient division into an early (May–June–July, henceforth MJJ) and a late rainfall season (August–September–October–November, henceforth ASON), with the latter often taken as representative of the entire Caribbean rainfall season due to the greater rainfall amounts and its coincidence with peak hurricane activity.

[3] An examination of Caribbean precipitation records indicates considerable interannual variability, some of which can be accounted for by variations in sea surface temperature anomalies (SSTAs) in the tropical Atlantic and/or tropical Pacific. (See the following section). The precipitation records also reveal significant differences between the interannual variability of the early versus late Caribbean rainfall seasons, which are not as easily explained if the controlling mechanisms of the late season are presumed to be those of the early season as well.

[4] In this paper we extend the work of a series of recent papers which examine the extent to which Caribbean rainfall is modulated by both the tropical Atlantic and the tropical Pacific. We show that for interannual variability the tropical oceanic region of dominant influence changes as the Caribbean rainfall season progresses. It is seemingly the tropical North Atlantic (TNA) that is of primary concern for interannual variability in the early season, with the tropical Pacific playing a secondary role, contributing only via its modifying effects on tropical Atlantic SSTs. By the late season, however, the role of the TNA diminishes significantly, with equatorial Pacific and equatorial Atlantic SSTAs becoming a significant influence.

[5] The following section contains a brief discussion of the known role of each of the tropical oceanic basins in

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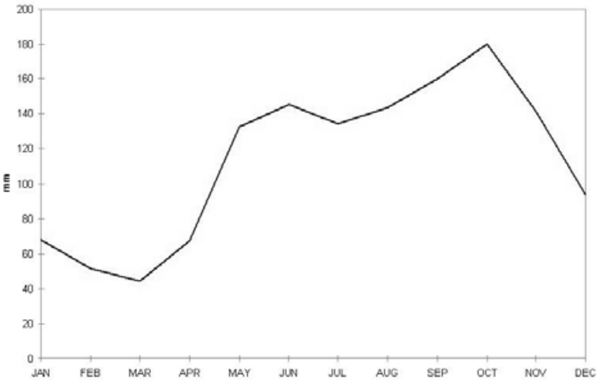

Figure 1. Mean monthly precipitation for the Caribbean. The time series is calculated from the 1958–1998 base period monthly means averaged over the area 10°–20°N, 65°–83°W. Units are mm/month.

determining Caribbean rainfall variability. Arising from the discussion we identify specific investigative tasks. The ensuing sections of the paper then (i) outline the data sets and methodology employed in the investigation (section 3) (ii) present the major results of the investigation (sections 4–7), (iii) examine a potential predictive model for early and late season Caribbean rainfall (section 8), and (iv) offer a physical mechanism to account for the changing oceanic influence with season (section 9). Section 10 offers a summary of our findings and examines their implications for the development of predictive schemes for Caribbean rainfall.

2. Background

2.1. Tropical Pacific Influence

[6] A number of studies to date have addressed year-to-year fluctuations in Caribbean rainfall, with much early emphasis placed on establishing an equatorial Pacific connection. As early as 1976, *Hastenrath* [1976, 1978] composited tropical Pacific SSTs (among other variables) for the 10 wettest and 10 driest Caribbean summers (July August), utilizing as an index of Caribbean rainfall an average of normalized rainfall records over 48 stations in Central and South America which kept records for the period 1911–1972. His results showed a drier Caribbean as coincident with higher SSTs in the equatorial Pacific, setting the stage for the (to become popular) dry Caribbean-ENSO relationship, while establishing the tropical Pacific as an influence on the region's rainfall.

[7] The results of Hastenrath are echoed in the global surveys of ENSO teleconnections produced by *Ropelewski and Halpert* [1986], *Ropelewski* [1987, 1989, 1996], and *Kiladis and Diaz* [1989]. These indicate a tendency toward a drier Caribbean during July to October of the mature El Niño year (i.e., just prior to the NDJ peak in equatorial Pacific SSTAs associated with El Niños), though the response is not as strong as might be inferred by Hastenrath's early work, especially when the Caribbean signal is compared to that of neighboring regions. *Rogers* [1988], and *Aceituno* [1988a] likewise reinforced the idea of a drying El Niño influence during the period of heaviest rainfall in the Caribbean.

[8] The common inference of the abovementioned studies is the restriction of the equatorial Pacific influence to the later Caribbean rainfall season, i.e., onward of July. In some cases (e.g. Hastenrath) this resulted from ascribing the characteristics of the late rainfall season (due to its larger accumulations) to the entire Caribbean rainy season, while in others (particularly the surveys) the restriction seems the byproduct of the research. The results suggest the tropical Pacific as primarily an interannual influence on late season Caribbean rainfall and it is an examination of this latter assertion (and by extension the lack of influence of the tropical Pacific on the early season), which is undertaken in this paper. We also examine the extent to which the Atlantic may be an interannual modulator during the same late season period given that none of the papers deliberately or otherwise do so.

2.2. Tropical Atlantic Influence

[9] Recently, *Chen et al.* [1997], *Taylor* [1999], *Giannini et al.* [2000], and *Chen and Taylor* [2002] address to varying extents influences on the rainfall rates in the early part of the rainy season (May through July). *Giannini et al.* [2000] use PCA analysis to extract relationships between leading modes of SLP and SST variability and Caribbean rainfall, and show that during the mature phase of ENSO a divergent surface flow dominates the eastern tropical Pacific and western tropical Atlantic. The dominant divergent pattern contributes to the previously mentioned tendency for a drier Caribbean during the later rainfall season. The corresponding weakened SLP gradient over the TNA also yields for the same region a weaker trade wind regime and the opportunity for a gradual warming of the sea surface [*Enfield and Mayer*, 1997]. Four to six months after the mature ENSO phase (i.e., boreal spring of the ensuing year), anomalously warm SSTs prevail over the TNA, which Giannini et al associate with the likelihood of a wetter Caribbean at the start of the new rainy season.

[10] The lag relationship between SSTAs of the tropical Atlantic and those of the equatorial Pacific is confirmed by *Curtis and Hastenrath* [1995], *Nobre and Shukla* [1996], and *Enfield and Mayer* [1997], who additionally note the spring TNA SSTs to be particularly enhanced between the 0°–20°N latitudinal band. Using a regional model centered over the Caribbean, *Taylor* [1999] argues that SST variations over this region during May–July alter Caribbean rainfall totals for the same period by producing a more favorable large-scale circulatory pattern for tropical wave development.

[11] While concurrent anomalies in the equatorial Pacific seem to influence late season Caribbean rainfall, TNA SSTAs (e.g. those induced by changes in the equatorial Pacific) seem a significant influence at the start of the Caribbean rainy season. *In this study we inquire as to whether tropical North Atlantic conditions, regardless of their cause, affect Caribbean rainfall in the same way.* Should this be true, it is a strong indication that even ENSO related early season rainfall anomalies [*Chen and Taylor*, 2002] are due directly to Atlantic warming and only indirectly to the Pacific ENSO. We additionally will show

the waning influence of the TNA with the onset of the late rainfall season.

2.3. A Tropical Atlantic–Pacific Gradient Relationship?

[12] Finally, a singular value decomposition (SVD) by *Enfield and Alfaro* [1999] shows the existence of a relationship between Caribbean rainfall and concurrent SSTAs in both the tropical Atlantic and tropical Pacific. An SVD decomposes the cross-covariance structures between two variable fields (in this case, SSTA and rainfall anomaly), and breaks down into separate modes according to the way in which the two variables are spatially and temporally associated with each other. Enfield and Alfaro find a strong response in the Caribbean to oppositely signed concurrent anomalies in the TNA and tropical Pacific, with the tendency being for enhanced rainfall over the Caribbean and Central America and a possible early onset to the rainy season under a warm Atlantic-cool Pacific scenario.

[13] Since Enfield and Alfaro considered a Caribbean rainfall season averaged over May–November (the entire rainfall season), it is not obvious whether the observed relationship between Caribbean rainfall and the oppositely signed oceanic anomalies is valid for the duration of the entire rainfall season, or a computational superposition of the tendency for a warm Atlantic to enhance rainfall in the early season, and a cool Pacific to do the same in the later season. An assessment of the tropical Atlantic–Pacific SST gradient influence throughout both seasons is undertaken. In this study we fashion an oceanic basin gradient index indicative of the difference between SST anomalies in the tropical Atlantic and Pacific, and assess its potential as a predictor and/or modulator of Caribbean rainfall activity in both the early and late season.

3. Data and Methodology

3.1. Data

[14] We take for our definition of the Caribbean basin a region covering 5°N and 25°N, and 90°W and 60°W. This is approximately the same region used by both *Giannini et al.* [2000] and *Chen et al.* [1997] in their respective analyses. The spatial and temporal variabilities of rainfall over the Caribbean are represented by the 0.5° × 0.5° monthly gridded analysis of *Magaña et al.* [1999] for the 1958–1998 period, from which the climatology for the same period has been removed.

[15] The Magaña data set is a hybrid of rainguage, satellite and model (reanalysis) data. Daily precipitation station data was compiled from the archives of (i) the National Center for Atmospheric Research (NCAR) for the southern United States, northern South America and the Caribbean Islands (ii) the Mexican Weather Service, and (iii) the National Weather Services of Central America. These are complemented with microwave sounding unit daily precipitation estimates over the oceans for the period 1979–1996 [*Spencer*, 1993], while for the pre-satellite era daily reanalysis precipitation estimates over the IntraAmerican Seas are utilized given the lack of any other source data in this region during this period.

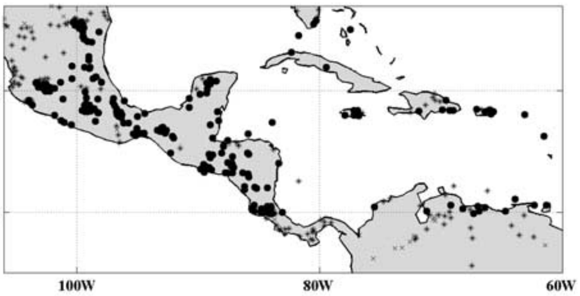

Figure 2. Map depicting correlations between stations with at least 18 years of monthly rainfall data between 1958 and 1995 and the nearest grid point of the Magaña rainfall data set. Key: solid circles, stations with significant correlations >0.8; asterisks, stations with significant correlations >0.5; and crosses, all other stations. Significant correlations are at the 95% level.

[16] Figure 2 shows that the blended analyses reasonably captures the precipitation variability over the Caribbean and Central American region. For Figure 2, monthly precipitation data from over 300 Central American and Caribbean stations, which possess more than 18 years of data between 1958 and 1995, are correlated with the nearest grid point of the gridded Magaña data set for the period of overlap. (The monthly station data set for the Caribbean and Central American region was independently compiled from the rain gauge data archives of multiple sources, including University of Costa Rica, University of Florida, National Climatic Data Center (NOAA, USA), and the Meteorological services of individual countries. The data set comprises 1128 stations with data over all or part of the period 1950–1995. The compilation was done under the auspices of an Initial Science Project (ISP-1), David B. Enfield (NOAA/AOML) principal investigator, funded by the Inter-American Institute for Global Change Research (IAI) through the U.S. National Science Foundation (Division of Atmospheric Sciences).) All the stations correlated positively (crosses in the diagram), with most correlating significantly at greater than 0.5 (*'s). Over 200 stations correlated significantly at greater than 0.8 (solid circles) including most of the coastal stations surrounding our defined region of interest. Comparison of the Magana data set with both the shorter Climate Prediction Center (CPC) merged rain gauge and satellite gridded data set [*Xie and Arkin*, 1997] and the smaller domain of the gridded University of the West Indies (UWI) station data set [*Chen and Taylor*, 2002], similarly yielded high significant correlations over 12 regions of the Caribbean defined in the latter study. In all cases statistically significant correlations are at the 95% level or higher, and significance is determined by the random phase method [*Ebisuzaki*, 1997], which accounts for serial correlation in the data.

[17] Though the resolution of the Magaña et al. data set is better than the 2.5° × 2.5° of the CPC data set used by *Enfield and Alfaro* [1999], we note that it is still too coarse to distinguish inhomogeneities across sharp orographic features in the region, and as such the results obtained in this study are representative only in a large-scale sense, and do not speak to relationships on smaller scales where orography may be important.

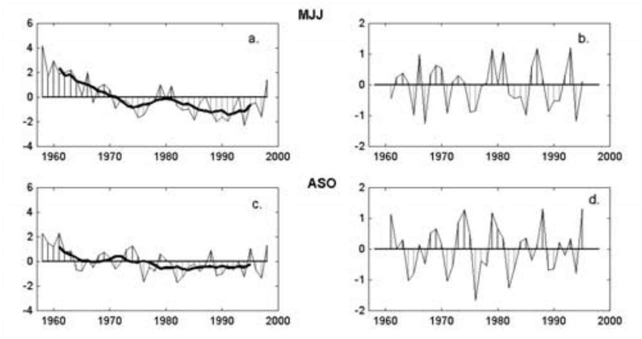

Figure 3. Time series of CPINDX (filled) and the smoothed CPINDX (bold line) for (a) MJJ and (c) ASO. The time series are derived from the Magaña data set for the 1958–1998 period, with climatology removed. CPINDX is an area average over the region 10°N–20°N and 83°–65°W. Units are cm. Figures 3b and 3d depict DCPINDX, (i.e., CPINDX minus the smoothed CPINDX).

[18] The SST anomaly (SSTA) data used are from the global analyses generated by *Kaplan et al.* [1998] (see *Enfield and Mestas-Nuñez* [1999] for a brief description). The Kaplan analyses are monthly deviations from a 1951–1980 climatology, for the period 1856–1891, and are gridded in 5° × 5° boxes. We examine SSTA data over a region spanning 20°S–45°N and 175°W–0°W. All other examined variables (vector wind) are from the NCEP-reanalyzed 2.5° × 2.5° X monthly gridded data set [*Kalnay et al.*, 1996].

3.2. Methodology

[19] We extract from the Magaña et al. data set two smaller data sets representing departures in the early and late rainfall seasons respectively. The early season data set consists of the gridded anomaly averaged over the 3 month period May, June, and July for each year, while the late season data set is the same but averaged over August, September and October. To characterize Caribbean rainfall variability, we extract from each seasonal data set a time series (CPINDX) consisting of a simple area average over the region 10°N–20°N, and 83°W–65°W. The area definition for the CPINDX is based on the distributions of variance explained by the first empirical orthogonal function (EOF) mode for the early and late season data sets. In the early season the first mode accounts for 38% of the total precipitation variance while in the late season it accounts for 23%. In both the early and late season the first mode explains large fractions (50–95% and 50–85% respectively) of the precipitation variance over sizable and nearly identical regions approximated by the area averaged. The CPINDX is an efficient representation of the overall Caribbean rainfall anomaly variability and has for each season a correlation higher than 0.95 with the first EOF of regional rainfall for the corresponding season.

[20] The time series of the CPINDX for the early and late seasons are shown in Figures 3a and 3c, respectively. To extract only an interannual component of the early and late season rainfall variability, the CPINDX for each season was smoothed by applying a 7 year running mean and the resulting smoothed time series (bold lines in Figures 3a and 3c) subtracted. As a consequence the time period under analysis in this paper is 1961–1995. It is the detrended CPINDX for each season (hereafter referred to as DCPINDX and shown in Figures 3b and 3d) which is analyzed in this paper.

[21] To determine the existence of a relationship between SSTAs in one or both of the tropical basins and rainfall variability in the early and late season, simple correlations are calculated and composites created. Correlations are calculated between the DCPINDX for each season and SST indices characterizing variability in the tropical Pacific (NINO3), the tropical north Atlantic (TNA) and the central equatorial Atlantic (EqATL) for seasons leading up to and including the rainfall season under analysis. NINO3 and TNA are as defined by *Enfield* [1996] and cover the regions 6°S–6°N and 150°–90°W and 6°S–22°N and 80°–15°W respectively. EqATL is the area average of SSTAs over the region 0°–15°W and 5°S–5°N. Composite maps of SSTAs are also generated for years when the DCPINDX for each rainfall season falls above or below given thresholds indicative of wet and dry conditions.

[22] Finally, we attempt to create separate predictive models for the early and late Caribbean rainfall seasons on the basis of the correlation and composite averaging. To do so gridded rainfall anomalies for each season are regressed on selected seasonal SSTA indices that exhibit the strongest relationships with the early and late rainfall season precipitation indices. If no difference exists between the controlling mechanism of the early and late seasons then the resulting models will be nearly identical.

[23] Selected results from the analyses are presented and discussed in the ensuing sections, with the early and late Caribbean rainfall seasons considered separately. We first however briefly examine the original and detrended time series of the early and late season rainfall.

4. CPINDX and DCPINDX

[24] The time series of Caribbean rainfall (CPINDX) for the early and late seasons (Figures 3a and 3c, respectively) show the Caribbean as prone to prolonged periods of anomalously wet conditions prior to the early 1970s, with a predominantly drier regime thereafter. The linear trend in the index is more pronounced in the early season than the late season, and is consistent with that seen in other analyses of Caribbean precipitation indices (see, e.g., T. C. Peterson, Recent changes in climate extremes in the Caribbean region, submitted to *Journal of Geophysical Research,* 2002, Figure 7). It is also well represented in many of the surrounding Caribbean coastal stations as suggested by the strong correlations of Figure 2.

[25] The shift around 1970 is also in phase with a similar change in the 10 year running average of North Atlantic SST and the onset of drier conditions over most of the continental United States [*Enfield et al.*, 2001]. This latter similarity suggests that both the U.S. and the Caribbean may be part of the same multidecadal covariability between rainfall and North Atlantic SSTA. If so, the phase similarity is more an initial indicator of early season rainfall sensitivity to SSTA variations in the North Atlantic than of the late season. This is also echoed in the power spectrum of the

Table 1. Correlations of the Detrended Caribbean Precipitation Index (DCPINDX) and Selected SSTA Indices in the Equatorial Pacific (NINO3), Tropical North Atlantic (TNA), and Equatorial Atlantic (EqATL)[a]

	NINO3				TNA				EqATL			
	NDJ	FMA	MJJ	ASO	NDJ	FMA	MJJ	ASO	NDJ	FMA	MJJ	ASO
MJJ	0.37[b]	0.35	0.11	...	0.10	0.50[b]	0.54[b]	...	−0.19	−0.02	0.22	...
ASO	0.17	0.08	−0.23	−0.36[b]	0.11	0.24	0.37[b]	0.19	0.21	0.43[b]	0.62[b]	0.53[b]

[a] DCPINDX is an area average over 10°–20°N and 65°–83°W, from which the long term trend has been removed. The Pacific and north Atlantic SSTA indices are as defined by *Enfield* [1996]: NINO3 (6°S–6°N) and 150°–90°W) and TNA (6°S–22°N and 80°–15°W). EqATL is the area average of SST anomalies over the domain 0°–15°W and 5°S–5°N. Correlations are for the 3 month periods preceding and up to the Caribbean rainfall season indicated by DCPINDX.

[b] Significant correlations.

MJJ CPINDX index (not shown) which indicates maximum power on decadal timescales (approximately 20 and 10 years respectively). SSTs of the TNA region are known to possess similarly strong decadal components with 10–20 year periodicities [*Carton and Huang*, 1994; *Mehta and Delworth*, 1995; *Chang et al.*, 1997].

[26] Figures 3b and 3d characterize the interannual variability of the early and late season rainfall, i.e., once the dominant linear trend has been removed. Though the two DCPINDX time series correlate significantly at +0.45, this is less than would have been anticipated if late season rainfall activity is indeed characteristic of the entire year. Several years exist when the rainfall anomalies in consecutive seasons of the same year are oppositely signed (see, for example, 1975, 1984, 1985, 1986, and 1991, and 1992) with 1986 and 1992 particularly noteworthy as an enhanced early season is followed by a depressed late season. The spectral analysis of the detrended series (not shown) likewise indicates notable difference between the two seasons. Whereas the spectrum for the late season possesses maximum power at periodicities of 6.7, 3.8, and 4.3 years, the early season exhibits several periodicities (6.7, 4.6, and 2.9 years) of comparable power, respectively.

5. Early Season

5.1. Correlations

[27] Table 1 depicts correlations between the DCPINDX for MJJ and the three derived SSTA indices averaged over consecutive 3 month periods. Significant correlations are indicated.

[28] The idea that early season rainfall is associated more with changes in SSTA in the tropical Atlantic than in the tropical Pacific is supported by the table. The MJJ DCPINDX is robustly correlated (+0.54) with SST anomalies in the TNA during MJJ as well as one season prior (FMA, 0.50). By contrast, the only significant correlation with the tropical Pacific occurs with the NDJ NINO3 index (+0.37). The concurrent presence of anomalies in the equatorial Pacific as might result from an ongoing El Niño or La Niña event appears unimportant for early season Caribbean rainfall, and the equatorial Atlantic offers little predictability either.

[29] Several studies referred to in section 2 establish a relationship between winter equatorial Pacific SSTAs and the early spring appearance of anomalies of similar sign in the TNA. The relationship is evident in the SSTA data set used as the correlation between the NDJ NINO3 and MJJ TNA indices is +0.66, and is similarly high and significant for NDJ NINO3 and FMA TNA (+0.56). It is likely, then, this relationship that is reflected in the MJJ DCPINDX-DJF NINO3 correlation, i.e., the equatorial Pacific influence on early season Caribbean rainfall arises via it's delayed alteration of SSTAs in a region of the TNA to which MJJ rainfall is particularly sensitive. Alternately stated: it is SST anomalies in the tropical North Atlantic which are of primary significance for interannual variation in early season Caribbean rainfall, with the possibility that these anomalies might result (though not always necessarily so) from changes in the equatorial Pacific a few months earlier.

[30] Supporting this interpretation, we note that the NDJ NINO3 correlation, being positive (+0.37), is opposite to the suggestion from *Enfield and Alfaro* [1999], whereby a stronger than normal rainy season is favored by a contemporaneously warm Atlantic and/or cool Pacific. The positive NINO3 correlation with a two season lead is consistent with the notion that the Pacific influence enters by proxy through the contemporaneous TNA, not directly with lag. By the time the ENSO-warmed TNA (late spring) begins to encourage strengthened early season rainfall, the Pacific anomalies have usually fallen to normal or below normal values, which is not inconsistent with the east-west seesaw relationship noted in Enfield and Alfaro.

[31] To determine quantitatively if the latter assertions are valid we perform a multiple regression with backward elimination for the MJJ DCPINDX using all prior season indices of NINO3 and TNA (i.e., NDJ and FMA) as predictors. In the procedure, predictor terms which do not satisfy an F test at or above the 95% significance level (serial correlation accounted for) are eliminated in an iterative procedure. If then two or more predictors are highly intercorrelated (such as DJF NINO3 and FMA TNA), only the one having the strongest relationship with the predictand is likely to survive elimination, regardless of their separate correlation with the rainfall index. Of the predictors only the FMA TNA is retained in the final model for MJJ rainfall. No additional variability in MJJ rainfall is therefore accounted for by considering the equatorial Pacific SSTA index once the TNA's role has been accounted for.

[32] Given the above, an attempt was also made to ascertain whether the robust +0.54 MJJ DCPINDX-MJJ TNA correlation is largely attributable to the Pacific's early season proxy influence on the TNA or to internal (i.e., non-ENSO related) variability of the TNA as well. To separate the contribution of the Atlantic versus Pacific to the variability of the TNA index, we regress the MJJ and FMA TNA indices on NDJ NINO3, and call the result NAN3. NAN3 represents the Pacific's influence on TNA SSTs for the respective quarter of the early season. NAN3

Table 2. As in Table 1 but for DCPINDX NAN3 and NANA[a]

	NAN3		NANA	
	FMA	MJJ	FMA	MJJ
MJJ	0.37[b]	0.37[b]	0.34[b]	0.41[b]

[a] NAN3 and NANA are as defined in the text and represent the ENSO and non-ENSO contributions to the TNA index, respectively.

[b] Significant correlations.

was then subtracted from TNA for each respective quarter and the residual called NANA. NANA is that portion of TNA variability due to the tropical Atlantic alone. The correlations of Table 1 were repeated for MJJ DCPINDX, NANA and NAN3. The results are shown in Table 2.

[33] Table 2 shows significant correlations between the early rainfall season index and NAN3 (i.e., the Pacific component of early season SSTA) for both FMA and MJJ. The correlations are predictably consistent with that between MJJ DCPINDX and NDJ NINO3 (Table 1). Table 2 however also shows significant correlations of roughly equal magnitude between MJJ DCPINDX and NANA for both FMA (+0.37) and MJJ (+0.41). It is variations in TNA SSTA which are significant for early season rainfall, whether they are due to ENSO influences or otherwise.

5.2. Composites

[34] To examine the contemporaneous state of the tropical Atlantic and Pacific when the early season is anomalously wet (dry) we construct composites of MJJ SSTA for years when the DCPINDX for MJJ falls in the upper (lower) tercile of all the values of DCPINDX. Figures 4a and 4b show respectively the wet and dry composites while Figure 4c shows the difference between Figures 4a and 4b with darkest shading highlighting regions of largest difference. Bold lines on the difference map denote regions where the mean wet and dry SSTAs are statistically different from each other at the 95% significance level using a *t* test.

[35] Consistent with a wet early season rainfall index is the appearance in the tropical Atlantic of a swath of anomalously warm water immediately north of the equator and through approximately 20°N (Figure 4a). The warm water spans the breadth of the tropical Atlantic, engulfs the Caribbean to the west and seemingly spills over into north tropical Pacific. Just north of the warm band, cooler SSTs (though still with positively signed anomalies) pervade the subtropical north Atlantic. When the DCPINDX for MJJ indicates dry conditions (Figure 4b), the TNA is opposite to that just described, with cold SSTAs replacing the previously noted warm anomalies of the tropical North Atlantic and warmer SSTs characterizing the subtropical north Atlantic.

[36] The difference map of Figure 4c suggests that for the Atlantic, the largest region of statistically significant difference between a wet and dry early season resides in the TNA between 0° and 20°N. North of this band, a smaller area is also significantly different, but is oppositely signed. The tropical Atlantic SSTA pattern of Figure 4c is nearly identical to the second EOF mode of Atlantic SST departures (strong TNA, little tropical south Atlantic) shown by *Enfield and Mayer* [1997], or the first unrotated principal component of tropical Atlantic SSTAs shown by *Vuille et al.* [2000].

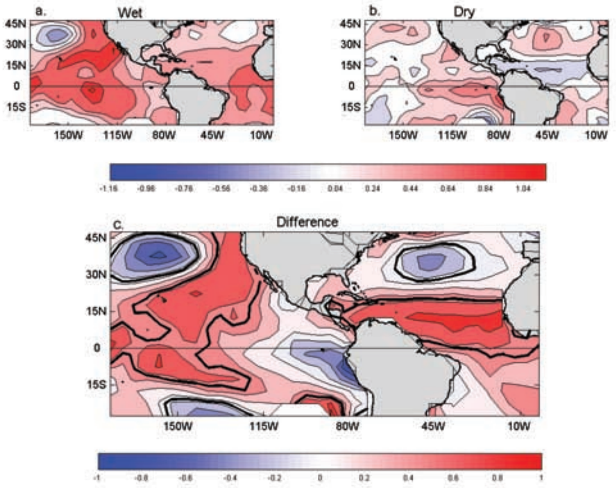

Figure 4. Composite map of MJJ Pacific and Atlantic SST anomalies: composites for (a) wet and (b) dry early season years (see text), (c) the difference between Figures 4a and 4b. Bold lines on Figure 4c indicate regions where the difference between mean SSTAs in Figures 4a and 4c are significant at the 95% significance level using a *t* test. Units are °C.

[37] Table 3 shows a contingency matrix classifying all the wet and dry early season years into three groups. The wet MJJ periods were classified as occurring in the year prior to the mature El Niño peak (NDJ) in equatorial Pacific SSTAs, subsequent to the peak, or neither, while dry MJJ periods were similarly classified with respect to La Niña (NDJ) extremes. The table shows that the effect of ENSO is to produce a wet (dry) early season in the year following an El Niño (La Niña) event, rather than in the year prior to the event. SST composite maps for MJJ, based solely on the post-ENSO events, reveal TNA extremes similar to those of Figure 4 and so also do the maps for non-ENSO wet/dry seasons. This is additional evidence that the direct effect on rainfall is through TNA temperatures regardless of whether they are of Pacific or Atlantic origin. The table entries also suggest that the rainfall-associated TNA extremes are about equally divided between the two sources (Pacific and internal Atlantic).

[38] In the Pacific two adjacent regions alternate sign when the early season changes from wet to dry conditions (see again Figure 4). The first is located in the midlatitudes

Table 3. Compilation of the Number of Wet (Dry) Early Season Years (as Defined in the Text) Which Occurred Prior or Subsequent to the NDJ Peak in Equatorial Pacific SSTAs Associated With the End of the El Niño (La Niña) Onset Year[a]

	El Niño			La Niña		
	Prior	Subsequent	Other	Prior	Subsequent	Other
Wet years	2	6	5			
Dry years				2	5	4

[a] Years that fell in neither category are classified as other.

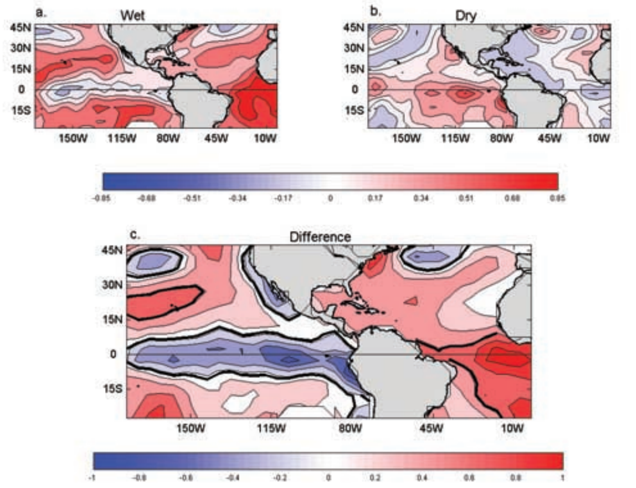

Figure 5. As in Figure 4 but for ASO rainfall and SST anomalies.

of the north Pacific (centered on 160°W, 40°N), and possesses negative SSTAs during a wet early season and vice versa. The second, located in the east north Pacific (centered on 130°W, 20°N), shows warm anomalies during the wet early season, with indications of the opposite when the Caribbean is dry. Both regions have difference composite amplitudes comparable to those observed in the tropical Atlantic in Figure 4c, yet linear correlation maps between the DCPINDX for MJJ and MJJ SSTA in the Pacific and Atlantic (not shown) indicate only the subtropical Pacific as possessing a significant relationship (−0.30) with early season rainfall. One possible implication is that tropical Atlantic transitivity is greater with respect to early season Caribbean rainfall, and hence a greater SST anomaly in the tropical Pacific is required to elicit the same rainfall response in the Caribbean as a TNA anomaly.

[39] We also note that the Pacific pattern of the wet composite is strongly reminiscent of the Pacific Decadal Oscillation (PDO). We suggest that the pattern likely arises because more of the wet early seasons which form the composite of Figure 4a occur subsequent to 1978, the year of phase shift in the PDO. The composite mean is therefore biased to reflect the decadal signature even though decadal frequencies have been high pass filtered from the precipitation index. By contrast the dry Caribbean early seasons that make up Figure 4b are evenly distributed between the pre and post-1978 period, and thus there is an absence of the PDO-like pattern in Figure 4b, and a more ENSO like pattern is observed.

6. Late Season

6.1. Correlations

[40] As presented for the early season, Table 1 also lists the correlations between the DCPINDX for ASO and the NINO3, TNA, and EqATL indices averaged over three month periods prior to and including the late season. Whereas the NINO3 index is concurrently correlated (−0.36) with the late season rainfall index, significant correlations with the TNA occur only for the preceding months. The EqATL index however indicates robust correlations between late season rainfall and concurrent and prior season SSTA in the central equatorial Atlantic.

6.2. Composites

[41] Repeating the composite analysis for the late season (Figure 5) reveals a relationship between Caribbean rainfall and a seesaw in equatorial Pacific and equatorial Atlantic SSTA. The pattern of Figure 5c is similar to the first SVD mode of *Enfield and Alfaro* [1999], which they associated with a weak tendency for dryness in the Caribbean.

[42] Considering the ocean basins separately, we first note a linear relationship between contemporaneous SSTA anomalies of the equatorial Pacific and late season Caribbean rainfall. For a dry late season Figure 5b reveals a central and eastern equatorial Pacific characterized by a band of positive SSTAs, with largest positive anomalies just west of the Galapagos Islands. During a wet late season the equatorial Pacific is by contrast cooler, resulting in a difference composite (Figure 5c) dominated by a narrow band of cool anomalies all along the equator. The pattern of Figure 5c is easily recognizable as that characteristic of an ENSO event. Table 4 groups the wet (dry) late season years according to their occurrence just prior (subsequent) to the NDJ peak of a mature La Niña (El Niño) event, and in an 'other' category. Approximately half of the years in each case occur just prior to the peak, indicating a sensitivity during the late rainfall season to a developing ENSO extreme.

[43] The correlations (Table 1), the composite maps (Figure 5) and the contingency matrix (Table 4) all show that heavy late season rainfall is associated with concurrent cool equatorial Pacific conditions (developing La Niña), and vice versa. This contrasts with the early season, which sees greater rainfall when the concurrent TNA is typically warm and El Niño reached a peak two seasons before. The concurrency and the opposite sign of the ENSO-DCPINDX relationship strongly suggest a direct influence on late Caribbean rainfall from the Pacific.

[44] In the tropical Atlantic, oppositely signed SST distributions are also associated with wet and dry late seasons. Positive SSTAs exist across the TNA (0°–20°N) inclusive of the Caribbean Sea for a wet late season, with these replaced by negative anomalies and a marked cooling of the Caribbean Sea during a dry ASO. The resulting difference composite (Figure 5c) does not however show the means in this region to be significantly different for the wet and dry scenarios.

[45] A reversal in the sign of the SSTAs for a wet and dry late season also occurs over the central and eastern

Table 4. Compilation of the Number of Wet (Dry) Late Season Years (as Defined in the Text) Which Occurred Prior or Subsequent to the NDJ Peak in Equatorial Pacific SSTAs Associated With the End of the La Niña (El Niño) Onset Year[a]

	La Niña			El Niño		
	Prior	Subsequent	Other	Prior	Subsequent	Other
Wet years	6	1	6			
Dry years				5	1	5

[a] Years that fell in neither category are classified as other.

equatorial Atlantic between 0°W and 15°W. The sign change in this equatorial region is opposite to that occurring in the equatorial Pacific, hence the previous reference to an equatorial 'seesaw' in SSTAs. Significantly warmer waters (i.e., than compared with the rest of the tropical North Atlantic) appear in this equatorial region during rainy phases, with cooler anomalies during the dry period. We note again the robust correlation between the late season rainfall and contemporaneous equatorial Atlantic SSTAs, which accounts for an even higher percentage of ASO DCPINDX variability (i.e., R^2) than the ASO NINO3 index.

[46] For both seasons therefore the Atlantic represents a significant modulator of Caribbean rainfall. For the late season however it is variations in the equatorial Atlantic that prove significant with little evidence of the strong TNA influence which proved important for the early season. Contemporaneous SSTAs in the equatorial Pacific also represent a significant influence on late season Caribbean rainfall, unlike the early season.

7. East–West Gradient Relationships

[47] The associations found with the tropical Atlantic and equatorial Pacific (particularly in the late season) raise similar questions to those posed by *Enfield and Alfaro* [1999], who suggested that rainfall in the Caribbean responds to specific configurations of the two tropical oceans. To determine if a concurrent configuration of opposite SSTAs in the two tropical basins is of any significance to Caribbean rainfall variability in separate seasons, we create two gradient indices. The first accounts for the importance of the TNA to early season rainfall, and is created by subtracting the TNA index from the NINO3 index (i.e., NINO3-TNA). We deem this new index the PACTNA. The second is predicated on the strong association between late season Caribbean rainfall and the central equatorial Atlantic (see Figure 5) and is created by subtracting EqATL from NINO3 (i.e., NINO3-EqATL). This latter index is called the PACEqATL index. In both instances, a positive value for the index suggests a warmer equatorial Pacific than Atlantic and vice versa. Each of the two new indices is further stratified by seasons (as in Table 1) and correlated with the DCPINDX for both early and late season with up to 3 seasons lag.

[48] It is noted that the creation of the two new indices does not imply that oppositely signed SSTAs in the two basins are ubiquitous in nature (as would be the case of a dipole or anticorrelated relationship between oceans). With the exception of NINO3 and EqATL during the early season (which correlate significantly at −0.32), there are no anticorrelations between the NINO3 index and the contemporaneous Atlantic indices (TNA, EqATL) for both the early and late season. We therefore take the correlations between the rainfall and seesaw indices as indicating the influence of east–west gradients at low latitudes on the Caribbean trade flow and associated tropospheric stability [*Knaff*, 1997]. The gradients may arise from anomalous extremes in either basin alone as well as from dipole configurations, although the latter will typically indicate a stronger rainfall response. The results of the correlations between DCPINDX and the PACTNA and PACEqATL indices are presented in Table 5 and discussed separately below.

Table 5. Correlations of the Detrended Caribbean Precipitation Index (DCPINDX) and Two Gradient Indices[a]

	PACTNA		PACEqATL	
	MJJ	ASO	MJJ	ASO
MJJ	−0.15	...	−0.01	...
ASO	−0.39[b]	−0.41[b]	−0.46[b]	−0.57[b]

[a] PACTNA is composed of the NINO3 index from which the TNA index has been subtracted. PACEqATL is composed of the NINO3 index from which EqATL has been subtracted.

[b] Significant correlations.

7.1. Equatorial Pacific–Tropical North Atlantic

[49] Only for the late season (ASO) are there statistically significant correlations between PACTNA and DCPINDX (Table 5). During this period PACTNA also accounts for a marginally higher percentage (R^2) of explained variance than that accounted for by the Pacific alone, but lower than that accounted for by the equatorial Atlantic (see the NINO3 and EqATL correlations in Table 1). The potential of the PACTNA index as a predictor of late season rainfall is also suggested by the significant correlation with DCPINDX with one season lag.

7.2. Equatorial Pacific–Equatorial Atlantic

[50] As with the PACTNA index, the correlation between early season Caribbean rainfall and PACEqATL is not significant. In the late season however, the correlation is higher than any of the previously analyzed relationships, i.e., than with TNA, NINO3, EqATL, or PACTNA, respectively. The percentage of explained late season rainfall variability is however only marginally higher than that explained by the EqATL index alone. The relationship suggested by the correlation is one whereby a warm equatorial Pacific and a cool equatorial Atlantic produces diminished rainfall over the Caribbean in the late season and vice versa. We note also that as a predictor of late season rainfall anomalies, PACEqATL holds greater promise than PACTNA given the higher correlation exhibited when it leads DCPINDX by one season.

[51] Finally, we refer again to the study of *Enfield and Alfaro* [1999] whose SVD mode 1 was marked by the presence of opposing SSTAs in the equatorial Pacific and Atlantic (similar to Figure 5c). As mentioned previously, they find that for a warm Pacific-cool Atlantic configuration there is only a weak (and statistically insignificant) tendency for drying in the Caribbean. The more robust association between oppositely signed equatorial anomalies and late season rainfall confirmed above strongly suggests that Enfeild and Alfaro's consideration of a Caribbean rainfall season averaged over the entire rainy period (May–November) might have biased their results. This is especially true inasmuch as we find no relationship between this SSTA configuration and the early season.

8. Predictive Models for Early and Late Season Rainfall

[52] Finally, in light of the results presented, we examine to what extent the SSTA indices can be used as the basis for predictive models of Caribbean seasonal rainfall. To do this,

we perform a multiple linear regression of gridded rainfall anomalies for each season on selected seasonal SSTA indices, using the results of the previous sections as a guide. In the regression procedure, predictor terms that did not satisfy an *F* test at or above the 95% significance level (serial correlation accounted for) were successively eliminated in an iterative backward procedure [*Draper and Smith*, 1966].

[53] For the early season we use FMA-TNA and NDJ-NINO3 as our predictors, given that these yielded the highest lagged correlation with early season Caribbean rainfall (see again Table 1). For the late season we attempted the regression technique using a combination of SST indices: MJJ-TNA, MJJ-NINO3, FMA- and MJJ-EqATL, MJJ-PACTNA, MJJ-PACEqATL. In the end, the results shown represent the regression on MJJ-TNA and MJJ-PACEqATL, as (i) of all the indices it is these which accounted for the largest percentage of explained variations in late season rainfall and (ii) the other potential predictors either did not survive the backward elimination procedure or they only survived at a few sporadic grid points. The results of the procedure are presented as a pair of maps for each season (Figure 6 and Figure 7), depicting the percent of rainfall variance explained by the final regression model (upper panel) and the predictors retained in the final model (lower panel) for each grid point. In the lower panels each predictor is signified by either light gray or dark gray, with black indicating areas were both predictors were retained by the procedure. White areas in the lower panels indicate areas where neither predictor survived elimination.

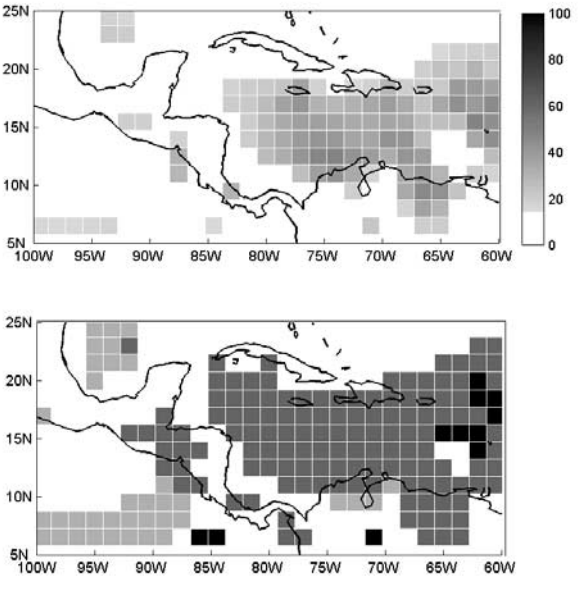

Figure 6. Results of a multiple linear regression with backward elimination of predictors, of the 1.5° by 1.5° gridded rainfall anomalies for MJJ on the DJF-NINO3 and FMA-TNA indices of sea surface temperature anomalies as described in the text. (top) Percent variance explained by the final model at each grid location (white is insignificant < 15%). (bottom) The model composition as being NINO3 only (light gray), TNA only (dark gray), or both indices (black).

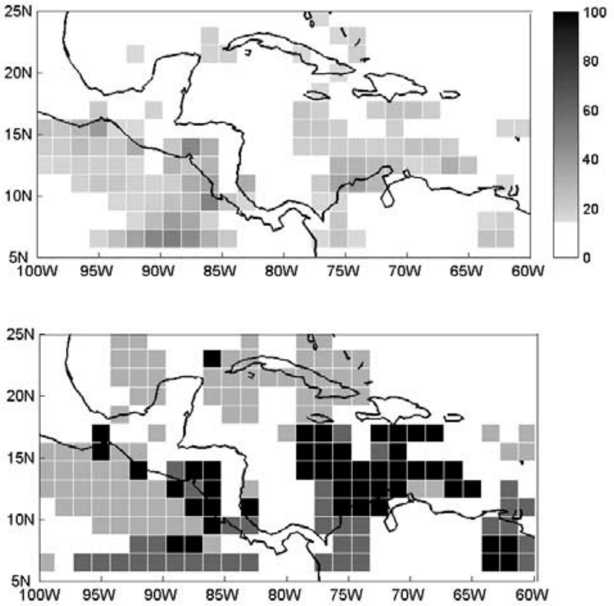

Figure 7. As for Figure 6 but for ASO rainfall anomalies regressed on the MJJ TNA and MJJ PACEqATL indices of SSTA. (bottom) Model composition is depicted as being TNA alone (light gray), PACEqATL alone (dark gray), or both indices (black).

[54] Note also that unlike the correlation analysis, the seasonal rainfall anomalies used in this section have not been detrended and represent deviations only from climatology. The trend was not removed so as to increase the degrees of freedom in the calculations. However, since the predictors are trendless the results should be unaffected. The anomalies have also been regridded to 1.5° × 1.5° squares to ease the computational load and the analysis is done for the full period of available data, i.e., 1958–1998. The models as presented in Figures 6 and 7 represent good indicators of the predictability of each rainfall season but are not meant to be taken as conclusive.

[55] For the early season a model was extracted over the entire Caribbean region south of 20°N (Figure 6). Over this region the tropical North Atlantic (dark gray) dominates the rainfall model, with explained variance ranging between 15% and 50%. Although ENSO-related variability survives in the near equatorial Pacific and a few grid points near the Lesser Antilles, the emergence of TNA SST anomalies as the likely dominant predictor of early season Caribbean again suggests that for most of the region during MJJ the equatorial Pacific is significant only via its alteration of the tropical North Atlantic. We also note a TNA influence on the early season rainfall of northern Central America.

[56] The overall predictive skill of the SSTA indices diminishes significantly with the evolution of the Caribbean rainfall season. Though both the PACEqATL and TNA indices are retained in the predictive model of late season (ASO) rainfall for a sizable portion of the central Caribbean basin, the percentage variance explained is significantly smaller (15–25%) than that explained by the early season models. This is also the case over the other contiguous regions of the Caribbean and Central America where one of

the two SST indices is retained in a predictive model instead of both. However, since our intention is to select the best model for the Caribbean, it is possible that better SST models exist for these other regions. The ASO retention of both predictors over the eastern Caribbean and the Pacific side of Central America is consistent with the importance of the interocean gradient relationship referred to earlier, as well as the results of *Enfield and Alfaro* [1999].

9. Evolution of the Rainy Season

[57] Our explanation for the shifting regions of dominant oceanic influence during the progression of the Caribbean rainfall season (i.e., TNA versus equatorial Pacific and Atlantic) is rooted in the climatological evolution of the SSTs of the tropical North Atlantic and Caribbean Sea. Figure 8 shows the climatological march of SST over the western hemisphere warm pool [*Wang and Enfield*, 2001] just prior to the start of the Caribbean rainfall season and at various points throughout the season. Shading denotes regions with SSTs > 26.5°C, a useful diagnostic for convective development [*Gray*, 1968]. The parallel lines on each figure straddle the 10°–20°N latitudinal band which *Goldenberg and Shapiro* [1996] denote the main development region (MDR) for easterly waves, which are convection centers that frequently mature into tropical storms and hurricanes. With easterly waves being the primary source of Caribbean rainfall, it is likely that atmospheric and oceanic changes in this region are of primary significance to Caribbean rainfall variability.

[58] Prior to the onset of the Caribbean rainfall season (March), SSTs of the tropical North Atlantic are well below 26.5°C, with only the far western Caribbean capable of supporting convective activity. At the onset of the Caribbean rainfall season (May), SSTs in excess of the 26.5°C threshold barely reach the leeward islands of the eastern Caribbean. The warm SSTs gradually spread eastward in the ensuing months and by August (the start of the late rainfall season) the region of favorable SST encompasses the entire Caribbean and extends through the mid TNA and the MDR. By October however, the entire TNA through to the west Coast of Africa is bathed in the warm waters that by now also exceed 28°C over much of the western and central tropical Atlantic.

[59] We consider the area of waters in excess of 26.5°C to be a significant factor in the explanation of Caribbean rainfall variability. Considering first the early season, we note that for this period only the Caribbean and western Atlantic basin are conducive to convective activity on the basis of the SST criterion. (This likely is a consideration when accounting for the smaller rainfall totals in MJJ than ASO). During years with an anomalously warm (cold) TNA, the region in excess of the SST threshold would however expand (contract) zonally across the region upwind/east (downwind/west) of the Caribbean. A more eastwardly extensive warm pool over the source region for Caribbean convection during warm TNA years would in turn favor greater convective development. *Knaff* [1997] shows that the tropospheric characteristics associated with a warm TNA, i.e., low pressure, low vertical shear, weak surface easterlies, high moisture content, and lower convective stability all favor increased convection. The sensitivity of the early rainfall season to anomalies in the TNA, particularly those across the 10°–20°N latitudinal band, therefore seems plausible.

[60] *Wang and Enfield* [2001] show that there is in fact considerable interannual variation in the size of the warm pool, with the range of interannual departures in its size being as large as the climatological size, and that the largest quartile of the warm pool area distribution is about twice the size of the smallest quartile. They also define a western hemisphere warm pool index consisting of the area of the TNA and eastern tropical Pacific in excess of 28.5°C. We correlate this index averaged over MJJ with the DCPINDX for the same period. Not surprisingly we find a significant correlation of +0.33. When the analysis is repeated for ASO the correlation does not prove significant.

[61] The waning influence of the tropical Atlantic and increasing significance of the equatorial Pacific in the late season is also linked to the spreading warm pool. By the late rainfall season, the entire breadth of the TNA including the MDR exceeds the threshold for convection by 1°–2°C. With the late season SSTs so high, even the largest (negative) TNA anomalies measured do not decrease SST below the range conducive for convection. Consequently only drastic (and uncharacteristic) changes in TNA temperatures can make the region unfavorable to rainfall with respect to SST. SSTs of the TNA do not exert primary control over rainfall variability in the late season.

[62] Once the SST criterion is met throughout the TNA, the major modulator of convective activity in the tropical Atlantic becomes the atmosphere, likely via the vertical shear of the horizontal wind. If strong, the vertical shear, defined as the difference in the vector winds at upper (200 mb) and lower (850 mb) troposphere, hinders the vertical development of convective systems which yield rainfall for the region [*Gray*, 1968].

[63] A connection between a warm equatorial Pacific and enhanced vertical shear in the Caribbean has long been established by those investigating global ENSO teleconnections [see, e.g., *Arkin*, 1982; *Aceituno*, 1988b] and further by numerous hurricane development studies [*Gray et al.*, 1994; *Goldenberg and Shapiro*, 1996]. Consequently, given an already climatologically warm TNA during the late season, the equatorial Pacific via the control it exerts on favorable or unfavorable shear conditions becomes a modulator of Caribbean rainfall, or otherwise stated, rainfall variability of the late season occurs primarily by shear modification of convective conditions as opposed to direct SST modulation during the early season. This may account for the inability to model as much of the region during the late season (Figure 7) based solely on SST criteria.

[64] In an attempt to explain the strong association between west-to-east SSTA gradient indices (PACTNA and PACEqATL) and late season rainfall, we examine difference composites for the 925 mb vector wind (Figure 9a) and the vertical shear vector (Figure 9b) for ASO. The composites are created in an identical manner to those of Figure 5c (i.e., using wet minus dry late season years) and are consistent with the oceanic SSTA state seen in Figure 5c, i.e., a cold equatorial Pacific but warm equatorial Atlantic. Vertical shear was calculated using respectively the difference between the u and v wind components at 200 mb and 850 mb.

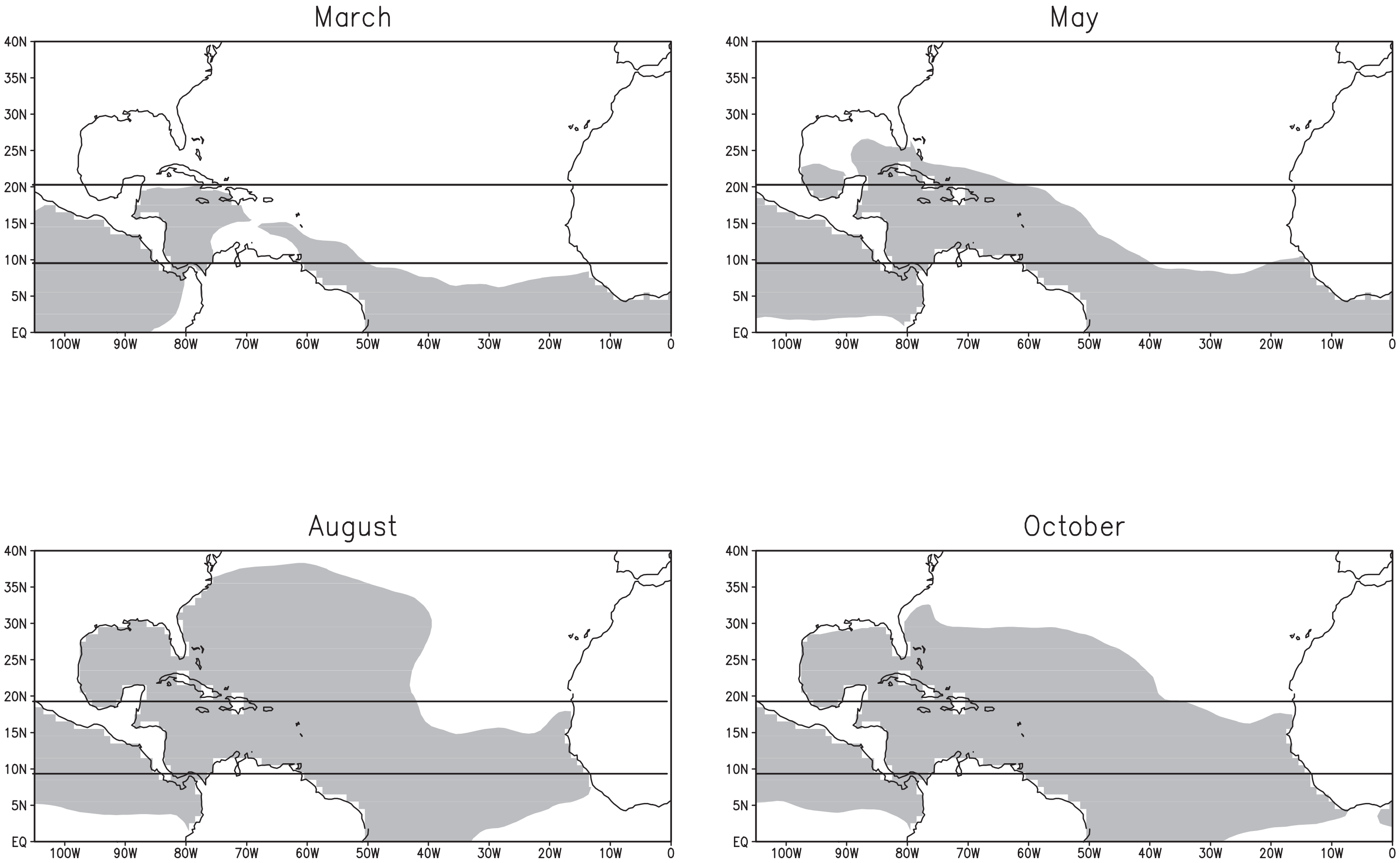

Figure 8. Climatological evolution of the tropical North Atlantic warm pool during the Caribbean rainy season. Shading depicts the regions of the tropical North Atlantic with waters warmer than 26.5°C. Parallel lines at 10°N and 20°N indicate the latitude band for tropical wave development, i.e., the main development region (MDR) [*Goldenberg and Shapiro*, 1996]. Climatology based on SST data from 1950 to 1999.

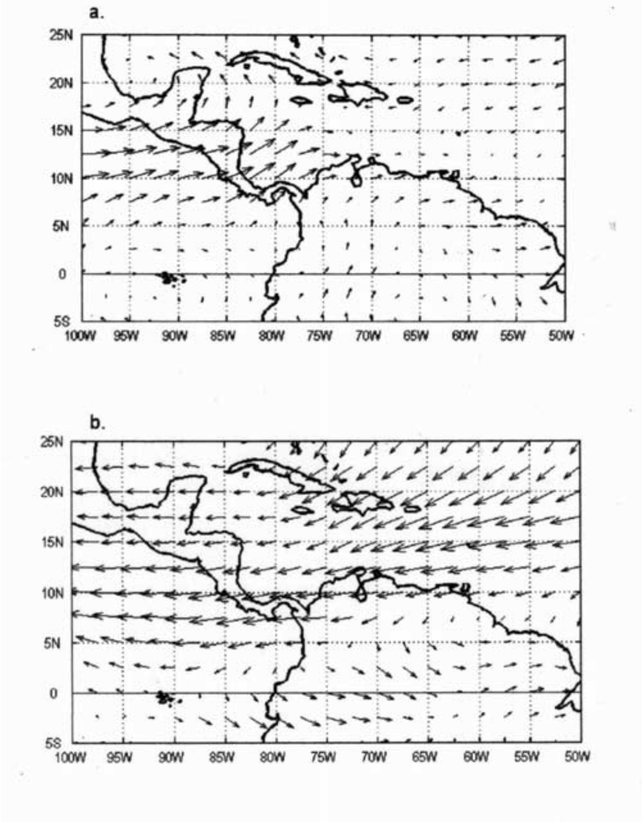

Figure 9. Map depicting the difference between ASO composites of (a) 925 mb vector wind and (b) vertical shear for years when the DCPINDX indicates wet and dry conditions.

[65] The anomalous low level wind vectors of Figure 9a are directed eastward across Central America and the southern Caribbean, from the east equatorial Pacific where they originate over the region of cold waters. They are deflected northward around the South American landmass and to the equatorial Atlantic where warm waters reside. The resultant weakening of the normal (easterly) Caribbean Low-Level Jet is one of the tropospheric factors associated with greater Caribbean rainfall and major hurricane development [*Knaff*, 1997]. Weakened trades in turn result in reduced heat loss in the surface mixed layer due to evaporation and entrainment, which besides favoring greater tropospheric moisture content, would also account for the positive SST anomalies observed in the tropical North Atlantic through 20°N during an enhanced late rainfall season (Figure 5a). We suggest that a similar mechanism explains the robust equatorial Atlantic relationship with late season rainfall, though the weakening of the Caribbean Low-Level Jet might not be as severe as when the west-east gradient is maximized by a La Niña occurrence.

[66] The relationship between low level wind strength and west−east SST gradients is further evident in the significant negative correlations between the ASO 925 mb zonal wind averaged over the CPINDX index region and the PACEqATL index for MJJ (−0.47) and ASO (−0.39). Significant correlations are also obtained between the ASO zonal wind and the PACTNA index for MJJ (−0.52) and ASO (−0.39).

[67] Weakened trades would also contribute to decreased vertical shear which characterizes the region under a cool Pacific and/or warm Atlantic scenario. The difference composite of Figure 9b shows the vertical shear vectors to be directed southwesterly over much of the Caribbean basin, indicating for a wet late season, a weakening of the normally strong southeasterly directed shear. As with the low level winds, strong relationships exist between the SST gradient indices and a contemporaneous vertical shear index averaged over the CPINDX region during the late season. The correlations with PACEqATL and PACTNA are +0.52, and +0.59 respectively with both being significant. The sign of the correlation indicates stronger shear over the Caribbean during a warm Pacific and/or cool Atlantic scenario (and vice versa), consistent with a diminished (enhanced) late season rainfall [*Knaff*, 1997].

[68] We interestingly find that the correlation between the vertical shear index and PACEqATL is not as strong in the early season (+0.33) as for the late season, though there is for MJJ a robust relationship between the shear index and contemporaneous TNA (−0.54). The implication is that vertical shear can be altered by SSTAs of one basin as well as by west−east gradient anomalies. For the early season then, the vacillation of SST between subcritical conditions for convection also determines the region of conducive vertical shear. This is further indication of the importance of the tropical north Atlantic to rainfall during this period.

10. Conclusions

[69] Because of the location of the Caribbean along a relatively land-free tropical strip, the interannual variability of its rainy season is strongly influenced by both the tropical Atlantic in which it resides and the nearby tropical and equatorial Pacific. Additional factors making the rainy season climate unique include: (1) position in the middle of a significant tropical warm pool; (2) low latitude with ageostrophy and direct circulation dynamics; (3) tropical convection mediated by vertical shear; and (4) a large suite of tropospheric characteristics that covary in a consistent manner. As has been shown in this paper, the relative influence of each oceanic basin changes as the rainfall season progresses in ways related to these factors.

[70] During the early part of the rainy season (MJJ), the tropical Atlantic led by the eastward march of warm SSTs, is under transition from a region not conducive to convective development to one favorable to such activity. During this period we show SSTAs of the tropical North Atlantic to be a primary modulator of Caribbean rainfall activity, a warm TNA being coincident with a more extensive warm pool and greater rainfall amounts, and vice versa. Concurrent anomalies in the equatorial Pacific prove insignificant in the interannual variability of early season rainfall, though anomalies in the same basin a few months prior are primary contributors to the warmings or coolings of the tropical North Atlantic during boreal spring [*Enfield and Mayer*, 1997]. Hence the equatorial Pacific can alter early season rainfall indirectly through its effect on the tropical Atlantic SST.

[71] During the late season (ASO), there is a distinct waning of influence of the tropical North Atlantic, with the equatorial Pacific and equatorial Atlantic becoming signifi-

cant influences on Caribbean rainfall. We suggest this is due to their association with an altered vertical shear structure in the tropical North Atlantic troposphere. The shear is related to the efficiency of convective development and is itself associated with other factors related to vertical stability [*Knaff*, 1997]. The importance of vertical shear in the late season as opposed to the early season arises out of the necessary precondition of a warm sea surface already being met throughout the tropical North Atlantic during the latter period. It is a cold equatorial Pacific or a warm equatorial Atlantic which is linked to enhanced late season rainfall.

[72] These findings provide empirical guidance for predicting Caribbean wet season rainfall. Though the Caribbean rainfall season runs from May to November, a meaningful predictive scheme must stratify the period into at least an early and late rainfall season, as the factors affecting each are different and possibly related to different mechanisms. A single predictive scheme for a mean rainfall season averaged over the entire period of May–November would therefore be inadequate and would in fact mask potentially strong signals.

[73] For the early season, the state of the tropical North Atlantic one to two seasons prior along with those factors known to alter the sea surface temperatures of the same region (including El Nino occurrences) would be viable candidates for any prediction scheme. A strong El Niño (La Niña) departure of the NINO3 index in November–December–January is an early harbinger of a wetter (drier) than normal early wet season. However, this relationship is mediated through SSTA in the TNA region, which may be independently affected by non-ENSO variability and is therefore a more reliable predictor in the boreal spring. For the late season, a cool equatorial Pacific and/or warm equatorial Atlantic one season in advance are optimal indicators for a wet late season, and if both conditions exist simultaneously the wet conditions are more likely. It is important to note that most of our results are based on analysis of only the interannual component of the early and late season Caribbean precipitation. It is likely however that Atlantic SSTA will affect rainfall in a similar way regardless of the cause or timescale, though the length of record did not allow us to determine this.

[74] Finally, we do see evidence of the effect of east–west gradients of SST anomalies in the tropical Pacific and Atlantic on Caribbean rainfall, with a tendency for a warm Atlantic-cool Pacific to favor Caribbean rainfall. We however note that the relationship seems true only for the late Caribbean rainfall season, with a zonal SSTA gradient index composed of the NINO3 and EqATL indices holding greatest promise for predicting rainfall anomalies during that period.

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References

Aceituno, P., On the functioning of the Southern Oscillation in the South American sector, part I, Surface climate, *Mon. Weather Rev.*, *116*, 505–524, 1988a.

Aceituno, P., On the functioning of the Southern Oscillation in the South American sector, part II, Upper-air circulation, *J. Clim.*, *2*, 341–355, 1988b.

Arkin, P. A., The relationship between the interannual variability in the 200 mb tropical wind field and the Southern Oscillation, *Mon. Weather Rev.*, *110*, 1393–1401, 1982.

Carton, J., and B. Huang, Warm events in the tropical Atlantic, *J. Phys. Oceanogr.*, *24*, 888–903, 1994.

Chang, P., L. Ji, and H. Li, A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions, *Nature*, *385*, 516–518, 1997.

Chen, A. A., and M. Taylor, Investigating the link between early season Caribbean rainfall and the El Niño + 1 year, *Int. J. Climatol.*, *22*, 87–106, 10.1002/joc.711, 2002.

Chen, A. A., A. Roy, J. McTavish, M. Taylor, and L. Marx, Using sea surface temperature anomalies to predict flood and drought conditions for the Caribbean, *COLA Tech. Rep. 49*, 24 pp., Cent. for Ocean Land Atmos. Stud., Calverton, Md., 1997.

Curtis, S., and S. Hastenrath, Forcing of anomalous sea surface temperature evolution in the tropical Atlantic during Pacific warm events, *J. Geophys. Res.*, *100*, 15,835–15,847, 1995.

Draper, N., and H. Smith, *Applied Regression Analysis*, 709 pp., John Wiley, New York, 1966.

Ebisuzaki, W., A method to estimate the statistical significance of a correlation when the data are serially correlated, *J. Clim.*, *10*, 2147–2153, 1997.

Enfield, D. B., Relationships of inter-American rainfall to tropical Atlantic and Pacific SST variability, *Geophys. Res. Lett.*, *23*, 3305–3308, 1996.

Enfield, D. B., and E. J. Alfaro, The dependence of Caribbean rainfall on the interaction of the tropical Atlantic and Pacific Oceans, *J. Clim.*, *12*, 2093–2103, 1999.

Enfield, D. B., and D. A. Mayer, Tropical Atlantic sea surface temperature variability and its relation to El Niño-Southern Oscillation, *J. Geophys. Res.*, *102*, 929–945, 1997.

Enfield, D. B., and A. M. Mestas-Nuñez, Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns, *J. Clim.*, *12*, 2719–2733, 1999.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble, The Atlantic multidecadal oscillation and its relationship to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080, 2001.

Giannini, A., Y. Kushnir, and M. A. Cane, Interannual variability of Caribbean rainfall, ENSO and the Atlantic Ocean, *J. Clim.*, *13*, 297–311, 2000.

Goldenberg, S. B., and L. J. Shapiro, Physical mechanism for the association of El Niño and West African rainfall with major hurricane activity, *J. Clim.*, *9*, 1169–1187, 1996.

Gray, W. M., Global view of the origin of tropical disturbances and storms, *Mon. Weather Rev.*, *96*, 669–700, 1968.

Gray, W. M., C. W. Landsea, P. W. Miekle Jr, and K. J. Berry, Predicting Atlantic basin seasonal tropical cyclone activity by 1 June, *Weather Forecasting*, *9*, 103–115, 1994.

Hastenrath, S., Variations in the low-latitude circulation and extreme climatic events in the tropical Americas, *J. Atmos. Sci.*, *33*, 202–215, 1976.

Hastenrath, S., On modes of tropical circulation and climate anomalies, *J. Atmos. Sci.*, *35*, 2222–2231, 1978.

Kalnay, E., et al., The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 3437–3471, 1996.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumethal, and B. Rajagopalan, Analysis of global sea surface temperatures 1856–1991, *J. Geophys. Res.*, *103*, 18,567–18,589, 1998.

Kiladis, G. N., and H. F. Diaz, Global climatic anomalies associated with extremes in the Southern Oscillation, *J. Clim.*, *2*, 1069–1090, 1989.

Knaff, J. A., Implications of summertime sea level pressure anomalies in the tropical Atlantic region, *J. Clim.*, *10*, 789–804, 1997.

Magaña, V., J. A. Amador, and S. Medina, The midsummer drought over Mexico and Central America, *J. Clim.*, *12*, 1577–1588, 1999.

Mehta, V. M., and T. Delworth, Decadal variability of the tropical Atlantic Ocean surface temperature in shipboard measurements and in a global ocean-atmosphere model, *J. Clim.*, *8*, 172–190, 1995.

Nobre, P., and J. Shukla, Variations of sea surface temperature, wind stress and rainfall over the tropical Atlantic and South America, *J. Clim.*, *9*, 2464–2479, 1996.

Rogers, J. C., Precipitation variability over the Caribbean and tropical Americas associated with the Southern Oscillation, *J. Clim.*, *1*, 172–182, 1988.

Ropelewski, C. F., Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation, *Mon. Weather Rev.*, *115*, 1606–1626, 1987.

Ropelewski, C. F., Precipitation patterns associated with the high index phase of the Southern Oscillation, *J. Clim.*, *2*, 268–284, 1989.

Ropelewski, C. F., Quantifying Southern Oscillation-precipitation relationships, *J. Clim.*, *9*, 1043 –1059, 1996.

Ropelewski, C. F., and M. S. Halpert, North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation, *Mon. Weather Rev.*, *114*, 2352 –2362, 1986.

Spencer, R. W., Global oceanic precipitation from the MSU during 1979–91 and comparisons to other climatologies, *J. Clim.*, *6*, 1301–1326, 1993.

Taylor, M., October in May: The effect of warm tropical Atlantic SSTs on early season Caribbean rainfall, Ph.D. thesis, Univ. of Md., College Park, 1999.

Vuille, M., R. S. Bradley, and F. Keimig, Climate variability in the Andes and its relation to tropical Pacific and Atlantic sea surface temperature anomalies, *J. Clim.*, *13*, 2520–2535, 2000.

Wang, C., and D. B. Enfield, The tropical western hemisphere warm pool, *Geophys. Res. Lett.*, *28*, 1635–1638, 2001.

Xie, P., and P. Arkin, Global precipitation: A 17-year monthly analysis based on observations, satellite estimates and numerical model outputs, *Bull. Am. Meteorol. Soc.*, *78*, 2539–2558, 1997.

A. A. Chen and M. A. Taylor, Department of Physics, University of the West Indies, Mona, Jamaica. (mataylor@uwimona.edu.jm)

D. B. Enfield, Physical Oceanography Division, NOAA/AOML, 4301 Rickenbacker Causeway, Miami, FL 33149, USA.