NOAA Technical Memorandum ERL AOML-80

STATISTICAL ASPECTS OF THE PRECIPITATION REGIMES AT MIAMI INTERNATIONAL AIRPORT (MIA) AND PALM BEACH INTERNATIONAL AIRPORT (PBI): 1961-1990

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Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

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Environmental Research Laboratories

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NOTICE

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STATISTICAL ASPECTS OF THE PRECIPITATION REGIMES AT MIAMI INTERNATIONAL AIRPORT (MIA) AND PALM BEACH INTERNATIONAL AIRPORT (PBI): 1961-1990

Stanley L. Rosenthal

ABSTRACT. Low-frequency components of the time series of mean annual precipitation for 1961-1990 at Miami International Airport (MIA) and Palm Beach International Airport (PBI) are closely in phase. The data show a decadal-scale variation with relatively high precipitation in the 1960's and 1980's and relatively low precipitation in the 1970's. This fluctuation is concomitant with a statistically significant decadal-scale fluctuation in tropical weather system frequency. MIA precipitation is systematically related to tropical weather system frequency on monthly and seasonal time scales but not so precisely that one can conclude a cause and effect relationship exists. Spectral analysis showed well marked peaks in the MIA and PBI spectra (computed from annual precipitation totals) at a period of 15 years. Both stations also showed considerable spectral intensity at a period of 10 years. Cospectral calculations indicated that the covariance of the MIA and PBI annual precipitation totals was primarily the result of fluctuations with periods of 10 years or more.

The annual numbers of cloudy days (NCLD), thunderstorm days (NTWS), days with measurable precipitation (NP.01), and the precipitation total for the rainiest day of the year (P24X) at MIA were correlated with those from PBI. Positive correlations (significant at either the 95% or 99% level) were obtained in all four cases. The time series of annual values of NCLD showed statistically significant negative trends at both stations. In contrast, the annual values of NP.01 showed positive trends at these stations. Thus, the number of days with measurable rain at these stations increased over these 30 years while the number of cloudy days decreased.

The time series of annual rainfall totals at both stations, when smoothed with five-year running means, showed maxima in the decade of the 1960's. Analyses of year-month cross sections showed that these maxima were the result of anomalously high rainfall in June and September-October during the later half of that decade.

1. INTRODUCTION

The heaviest rains in south Florida are produced by mesoscale convective systems embedded in synoptic-scale disturbances (Riehl, 1979). As is well known, the synoptic-scale disturbances that impact south Florida rainfall in the cooler (dry) months are usually extratropical baroclinic zones, while those in the warmer (rainy) months are generally weather systems of tropical origin. In addition to the rain associated with synoptic-scale disturbances, about 57% of the summer rainfall results from sea-breeze convergence on undisturbed days (Burpee and Lahiff, 1984).

While precipitation totals in south Florida have substantial station-to-station variability as the result of local effects, Rosenthal (1993) found that the time series of annual precipitation totals at Miami International Airport (MIA) and Palm Beach International Airport (PBI) had similar interannual variations during 1961-1990 despite the fact that these stations are approximately 75 miles[1] apart. The present paper examines the relationships between the precipitation regimes at these two stations in greater detail. Such research is motivated by the need (well recognized in recent years[2]) to gain a better understanding of regional climate and its decadal-scale temporal fluctuations.

2. PRELIMINARY ANALYSES AND HOMOGENEITY

Figure 1 shows the location of MIA and PBI and the cooperative stations at Homestead (HOM) and Hialeah (HIA). Tables 1 and 2 show the annual precipitation totals for MIA and PBI for 1961-1990 and their normalized (by subtracting the 30-year mean and dividing by the standard deviation) values. The 30-year annual mean rainfall at PBI is seen to be 4.6 inches greater than at MIA. This difference is statistically significant at the 99% level based on Student's t-test (Hoel, 1954) and at the 95% level based on the nonparametric Wilcoxon signed rank test (Ott, 1988).

Figures 2a and 2b show the MIA and PBI data in graphical form. The Spearman correlation coefficient[3] between the annual totals of the two 30-year samples is 0.71, which is significant at the 99% level. Smoothing of the annual precipitation totals with five-year running means (Figure 2c) reveals decadal-scale fluctuations that are closely in phase. Relatively moist conditions are found in the late 1960's and in the early to middle 1980's and relatively dry conditions are found at other times. (The Spearman correlation coefficient between the MIA and PBI smoothed time series is 0.91, which is significant at the 99% level.) A similar decadal-scale pattern was also found in the rainfall data for the Florida southeast coast discussed by Hanson and Maul (1991).

When the data are averaged over decades (Table 3), we see that MIA and PBI both had greater rainfall in the 1960's and in the 1980's than in the 1970's. This interdecadal precipitation pattern is concomitant with an interdecadal variability of nearby tropical weather system activity. The latter was determined by constructing a circle of 200 nautical miles radius around MIA and counting the number of tropical weather systems (ranging in intensity from tropical depression to hurricane) given by Neumann *et al.* (1987) that passed through this circle during 1961-1990. The results (last line of Table 3) show an interdecadal variation similar to that of the precipitation. A binomial test (Rosenthal, 1991) was used to determine the probability that the difference in the tropical weather system totals between decades could occur by chance. These probabilities were found to be .03 when 1971-1980 was compared to 1961-1970 and .04 when 1971-1980 was compared with 1981-1990.

To continue the examination of relationships between rainfall and tropical weather system activity, precipitation totals were calculated for the months May-November for each year of 1961-1990 and the years were ordered by the ranks of these seven-month precipitation totals. The frequency of tropical weather systems (obtained as described above) was then determined for the wetter and drier 15 years of the 1961-1990 sample and the procedure was repeated for each individual month of the May-November period. The results are shown in Table 4. Although not statistically significant at normally accepted levels, Tables 3 and 4 suggest that the interdecadal variation of precipitation at MIA and PBI during 1961-1990 is associated with a similar interdecadal variation of tropical weather system frequency.

Table 5 shows comparisons of precipitation statistics for the station pairs MIA/PBI, MIA/HIA, and MIA/HOM. We see that neither the differences between precipitation totals at station pairs nor the phase relationships between station pairs are simple functions of the distance between the stations. For example, the distance between MIA and HOM lies between that of MIA/HIA and MIA/PBI but the MIA/HOM station pair has the smallest difference in mean precipitation and, at the same time, the smallest correlation.

The official rain gauges at MIA and PBI were moved, respectively, by about 9,200 ft and 4,750 ft on 1 March 1977 (U.S. Dept. Comm., 1990a,b). Three different statistical procedures were used to test the possibility that these moves created inhomogeneities in the precipitation data. First, the slopes of least-square linear trend lines fit to the MIA and PBI annual precipitation totals were tested for significant differences from zero by Student's t-test (Hoel, 1954, p. 231). In each case the slope was found to be insignificant at even the 90% level. In the second test, the mean annual precipitation for the periods before and after 1977 were tested for significant differences by the Student t-test (Hoel, 1954, p. 227) and

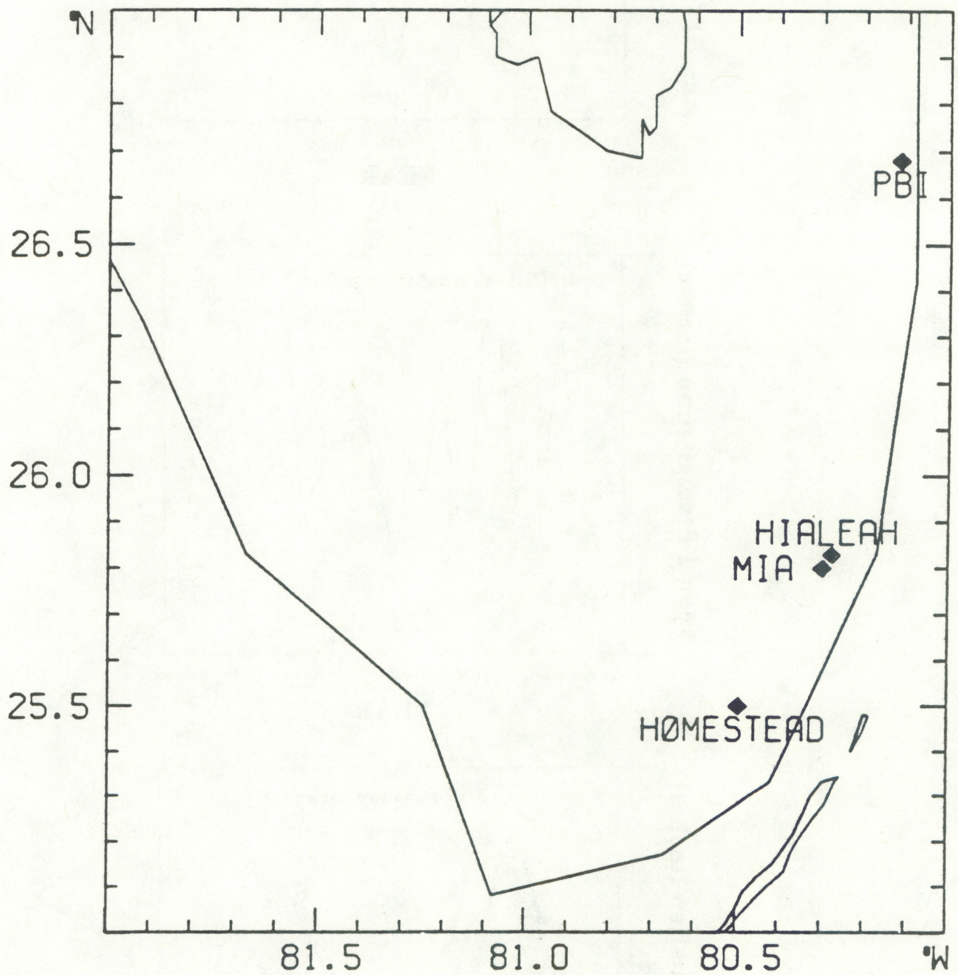

Figure 1. Map of south Florida showing the location of the stations used in this study. MIA and PBI are the first order National Weather Service (NWS) stations at, respectively, Miami International Airport and Palm Beach International Airport. Hialeah and Homestead are NWS cooperative stations at those locations.

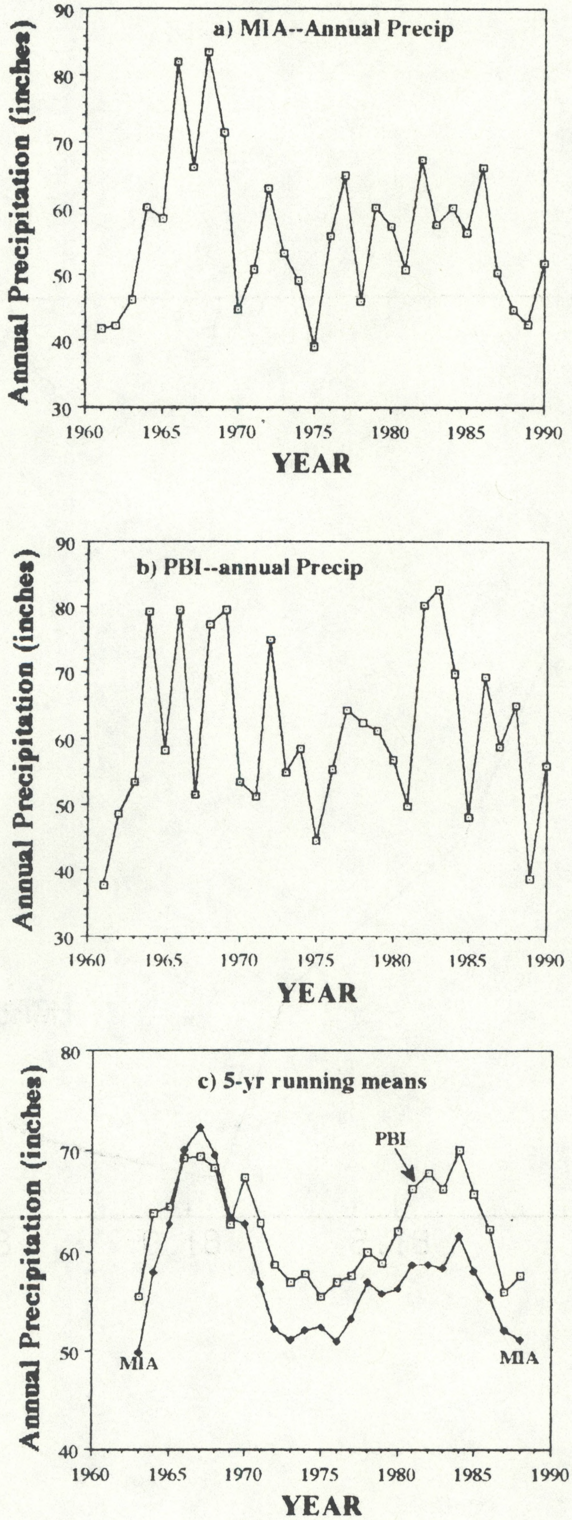

Figure 2. Annual precipitation: (a) MIA; (b) PBI; and (c) five-year running means for MIA and PBI.

Table 1. Miami International Airport (MIA) annual rainfall in inches.

Year	Rainfall (inches)	Normalized	Year	Rainfall (inches)	Normalized
1961	41.7	-1.3	1976	55.9	0.0
1962	42.3	-1.2	1977	64.9	0.8
1963	46.1	-0.9	1978	45.8	-0.9
1964	60.2	0.4	1979	60.1	0.4
1965	58.4	0.2	1980	57.3	0.1
1966	82.1	2.3	1981	50.8	-0.5
1967	66.2	0.9	1982	67.4	1.0
1968	83.4	2.5	1983	57.4	0.1
1969	71.5	1.4	1984	60.0	0.4
1970	44.7	-1.0	1985	56.3	0.0
1971	50.7	-0.5	1986	66.1	0.9
1972	63.1	0.6	1987	50.3	-0.5
1973	53.2	-0.3	1988	44.6	-1.0
1974	49.9	-0.6	1989	42.6	-1.2
1975	39.1	-1.5	1990	51.7	-0.4

Mean annual rainfall = 56.1; Standard deviation = 11.1

Table 2. Palm Beach International Airport (PBI) annual rainfall in inches.

Year	Rainfall (inches)	Normalized	Year	Rainfall (inches)	Normalized
1961	37.7	-1.8	1976	55.3	-0.4
1962	48.6	-1.0	1977	64.3	0.3
1963	53.3	-0.6	1978	62.2	0.1
1964	79.3	1.5	1979	61.2	0.0
1965	58.3	-0.2	1980	56.7	-0.3
1966	79.8	1.5	1981	49.7	-0.9
1967	51.5	-0.7	1982	80.4	1.6
1968	77.4	1.3	1983	82.7	1.8
1969	79.8	1.5	1984	69.8	0.7
1970	53.3	-0.6	1985	48.0	-1.0
1971	51.3	-0.7	1986	69.3	0.7
1972	75.2	1.2	1987	58.7	-0.2
1973	54.8	-0.5	1988	64.9	0.3
1974	58.5	-0.2	1989	38.7	-1.8
1975	44.4	-1.3	1990	55.8	-0.4

Mean annual rainfall = 60.7; Standard deviation = 12.6

Table 3. Mean annual precipitation (inches) at MIA and PBI as a function of decade. Bottom line is frequency of tropical weather systems (see text for definition) per decade.

	1961-1970	1971-1980	1981-1990
MIA	59.6	53.9	54.5
PBI	62.1	58.4	61.8
Number of tropical weather systems	18	8	16

Table 4. Number of tropical weather systems in wetter 15 years and drier 15 years during May-November 1961-1990 and for each month in May-November. Probabilities given in parentheses are binomial probabilities of the indicated number of occurrences or less.

Month	Wetter 15 Years	Drier 15 Years
May-November	25	17 (p = .12)
May	1	0 (p = .50)
June	6	2 (p = .14)
July	1	0 (p = .50)
August	7	4 (p = .27)
September	9	3 (p = .07)
October	4	3 (p = .49)
November	0 (p = .25)	2

Table 5. Precipitation statistics (1961-1990) for the indicated station pairs. Asterisks denote statistical significance at the 99% level (***), the 95% level (**), and the 90% level (*).

Station Pair	MIA/PBI	MIA/HOM	MIA/HIA
Variable distance (miles)	75	28	7
Raw Data			
Mean annual precipitation difference (inches)	-4.6***	-2.7	-6.9***
Spearman correlation	.71***	.42**	.95***
Smoothed Data			
Mean annual precipitation difference (inches)	-4.8***	-2.4*	7.0***
Spearman correlation	.91***	.57***	.94***

by the nonparametric Mann-Whitley test (Ott, 1988, p. 183). Neither test showed statistically significant differences. In the third test, the two data sets were checked for trends by the nonparametric Mann-Kendall test (WMO, 1966) and, again, neither time series showed a statistically significant trend. It was, therefore, concluded that no obvious inhomogeneities had resulted from relocation of the rain gauges.

3. INTERANNUAL VARIABILITY

In section 1 we showed that the interannual variations of precipitation at MIA and PBI contained decadal-scale fluctuations with maxima in the 1960's and 1980's and a minimum in the 1970's. Spectral analyses of the MIA and PBI annual precipitation totals were carried out in order to quantify these results. The calculations followed the procedure outlined by Panofsky and Brier (1958). The time series were first detrended by subtracting a least-square trend line. The data were then pre-smoothed with a (.25, .50, .25) three-point smoother and serial correlation coefficients to lag 15 were calculated from the detrended, pre-smoothed data. By use of the formulae given by Panofsky and Brier (1958), the serial correlation coefficients were Fourier transformed to obtain preliminary spectral estimates which, also following Panofsky and Brier (1958), were smoothed with the (.25, .50, .25) three-point smoother. Cospectral calculations were performed in the same way with lagged cross correlations replacing the serial correlations.

Figure 3a shows the serial correlation coefficients after the data have been pre-smoothed with the three-point smoother. Figure 3b shows the serial correlation coefficients after the data are pre-smoothed using simple five-year running means. The dominance of a fluctuation with a period of near 15 years is clear cut at both stations. The serial correlation coefficients at these two stations are remarkably similar. The spectra for both stations show distinct spectral peaks at periods of 15 years (Figures 4a and 4b) but there is also substantial power at a period of 10 years. In addition, PBI (Figure 4b) shows a secondary peak in the 4.28-5.0 year range. The difference in spectral intensity between MIA and PBI at a period of five years is significant at the 95% level based on the Chi-square test described by Panofsky and Brier (1958, p. 145).

The differences between the MIA and PBI spectra are even more pronounced when the annual precipitation totals are not pre-smoothed (Figures 4c and 4d). Here we see that the PBI peak at 4.28-5.0 years is slightly more intense than the decadal-scale (10-15 year) peak. In the case of MIA, the spectrum (Figure 4c) shows only a minor "bump" at these periods. Hanson and Maul (1991) examined rainfall records averaged over southeast Florida coastal and near coastal stations and found significant peaks in the five to six year band which they attributed to El Niño. This does not appear to be the explanation of the PBI peak at 4.28-5.0 years since one would expect a large-scale event such as El Niño to provide similar impacts at both MIA and PBI.

Figures 4e and 4f show the cospectrum between the MIA and PBI annual precipitation totals based on, respectively, data pre-smoothed with the (.25, .50, .25) smoother and unsmoothed data. As would be expected from the material presented above, the correlation between the two stations is primarily due to fluctuations with periods of 10 years or greater and, in fact, these fluctuations account for 80% of the covariance in the pre-smoothed data. In the case of the unsmoothed data, periods of 10 years or longer account for 50% of the covariance.

The NOAA data tabulations used in this research (U.S. Dept. Comm., 1961-1990a,b) contain four variables that provide fuller descriptions of precipitation regimes than is possible with precipitation totals alone. These variables are: (1) the number of cloudy days (80% or greater sky coverage averaged from sunrise to sunset) per month (NCLD); (2) the number of thunderstorm days per month (NTWS); (3) the number of days per month with precipitation greater than .01 inches (NP.01; also known as the number of days with measurable rain); and (4) the largest accumulation of precipitation in a 24-hour period during each month (P24X).

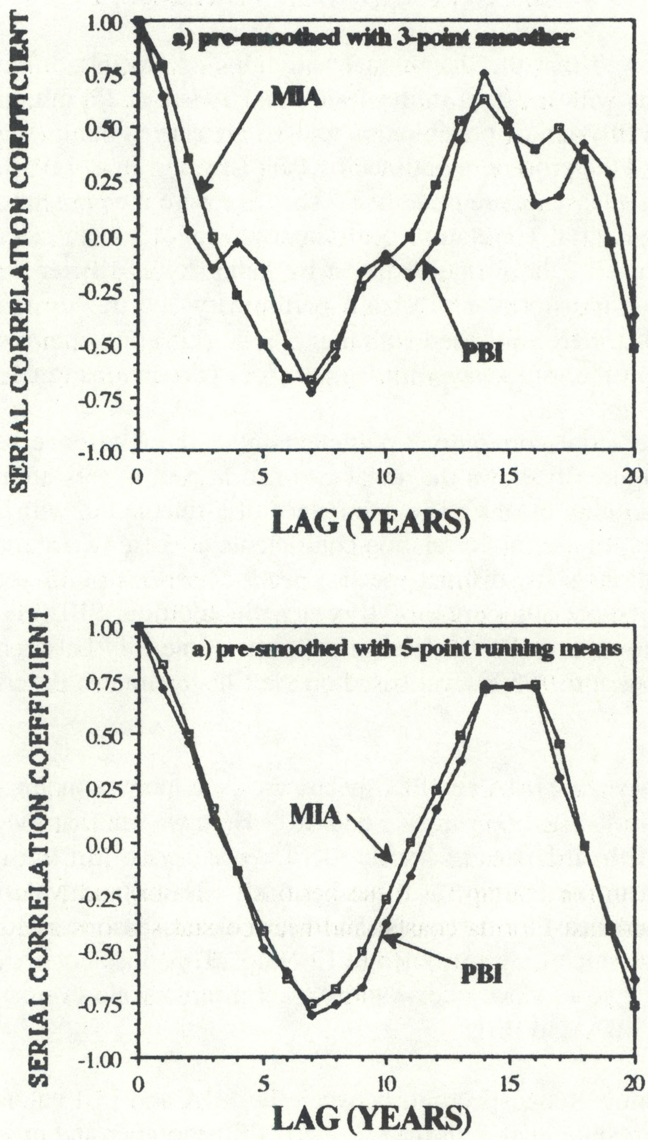

Figure 3. MIA and PBI annual precipitation serial correlation coefficients: (a) annual precipitation pre-smoothed with three-point smoother; and (b) annual precipitation pre-smoothed with five-year running means.

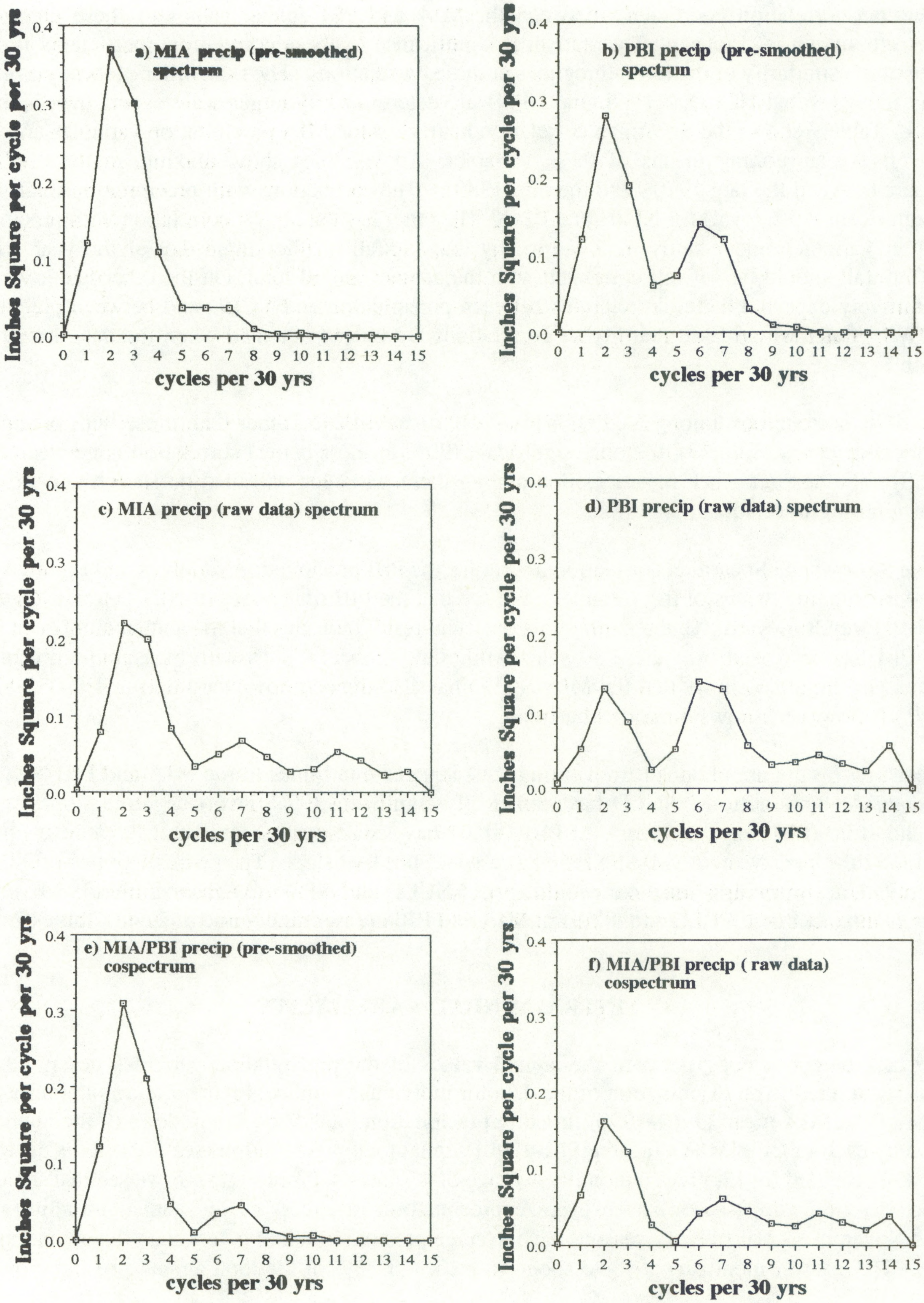

Figure 4. Spectra and cospectra of annual precipitation totals at MIA and PBI. Description of graphs is given by the section captions. "Pre-smoothed" indicates that the raw data have been smoothed by the (0.25, 0.50, 0.25) three-point operator.

Spearman correlation coefficients between the MIA and PBI annual values of these precipitation variables are shown in Table 6. The statistical significance of these correlation coefficients is further evidence of the similarity of the rainfall regimes at these two stations. The rank order of these correlations probably indicates that NCLD, NTWS, and NP.01 are determined by larger scale events than is the case for P24X. Table 7 shows the Spearman correlation matrix for the MIA precipitation variables and Figure 5 shows five-year running means of these variables. All variables show maxima in the 1960's and somewhere between the late 1970's and the mid 1980's. The correlations with precipitation totals (Table 7) are significant (99% level) for NP.01 and P24X. The latter has the largest correlation with precipitation of the four variables under study. It is surprising that rainfall on the single day of the year with the greatest rainfall should be so well correlated with the annual rainfall total. On the other hand, we might have intuitively expected better correlations between precipitation and NCLD and between precipitation and NTWS. Later we will see that higher correlations are indeed obtained when the data are stratified by month.

When the correlations among NCLD, NTWS, NP.01, and P24X, other than those with precipitation totals, are considered (Table 7), the only significant (90% level or better) correlation is between NTWS and NP.01. The apparent lack of association among these variables will also be shown later to be the result of ignoring intra annual variations.

Table 8 shows the Spearman correlation matrix for the PBI precipitation variables and Figure 6 shows the five-year running means of the variables. We see that the PBI time series of NCLD trends downward while NP.01 trends upward. This seemingly inconsistent result indicates that the annual number of cloudy days at PBI has decreased over these 30 years while the number of days with measurable precipitation has increased. Figure 5 shows that the MIA NCLD has also trended downward during 1961-1990. The MIA NP.01, however, shows no particular trend.

Interesting results are obtained from fitting least squares trend lines to the MIA and PBI NCLD and NP.01 data. At both stations, NCLD has statistically significant (99% level) negative slopes of -1.24 (MIA) and -1.20 (PBI) days per year. At PBI, NP.01 has a statistically significant (95% level) positive slope of 0.67 days per year. At MIA, NP.01 has a small positive slope. The positive slopes of NP.01, as already noted, are surprising since one would expect NCLD and NP.01 to behave similarly. Even more surprising is the fact that NCLD and NP.01 at MIA and PBI are essentially uncorrelated (Tables 7 and 8).

4. INTRA ANNUAL VARIABILITY

The lack of consistency between the annual values of the precipitation variables described in the previous section led to an examination of the data for individual months. Figure 7 shows the intra annual variation of the MIA mean (1961-1990) monthly precipitation totals[4] and the fraction of the annual total provided by each month. MIA's mean (1961-1990) annual total precipitation (see Table 1) is 56.1 inches which, when divided by 12, gives a monthly average of 4.7 inches. From Figure 7, we see that the months May-October (the rainy season) have average precipitation in excess of the annual monthly average whereas November-April (the dry season) have average precipitation that is less than the annual monthly average. The six wet months contribute about 42 inches or 75% of the total annual precipitation.

The double peak in the MIA summer rain is a well-known feature of the south Florida and Cuban annual rainfall cycle that has been discussed by Riehl (1979). Table 9 shows that the precipitation differences between June and July and between June and October are statistically significant at the 99% level. The differences between June and August and between June and September have weaker statistical significance or no significance at all. According to Riehl (1979), the double peak in the MIA summer rainfall is the result of a mean upper air trough that extends southward from middle latitudes and lies over Cuba and Florida in early summer, migrates westward to the Gulf of Mexico in the middle summer, and

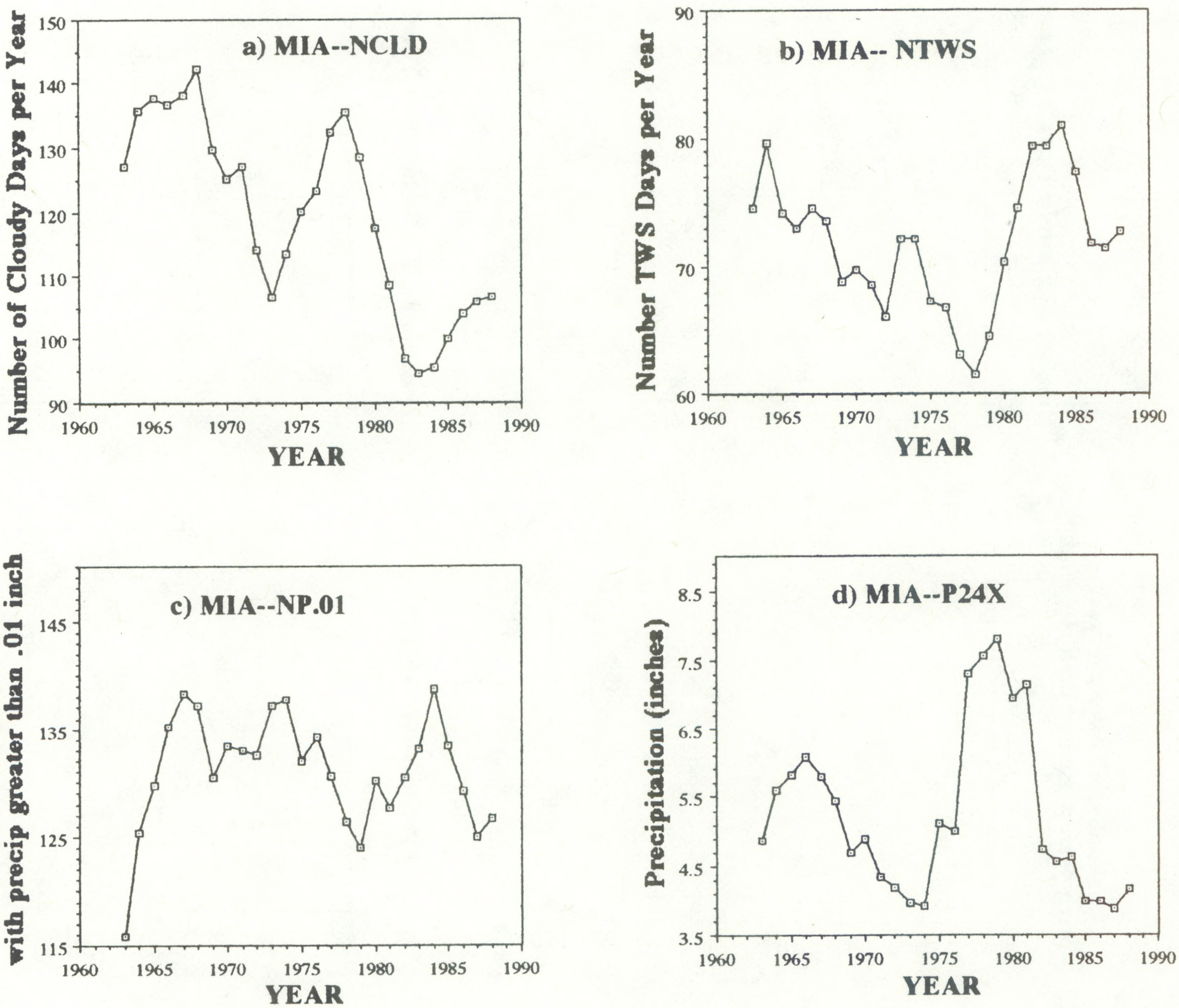

Figure 5. Five-year running means of MIA precipitation variables: (a) number of cloudy days per year (NCLD); (b) number of thunderstorm days per year (NTWS); (c) number of days per year with precipitation greater than .01 inches (NP.01); and (d) precipitation on day of year with greatest precipitation (P24X).

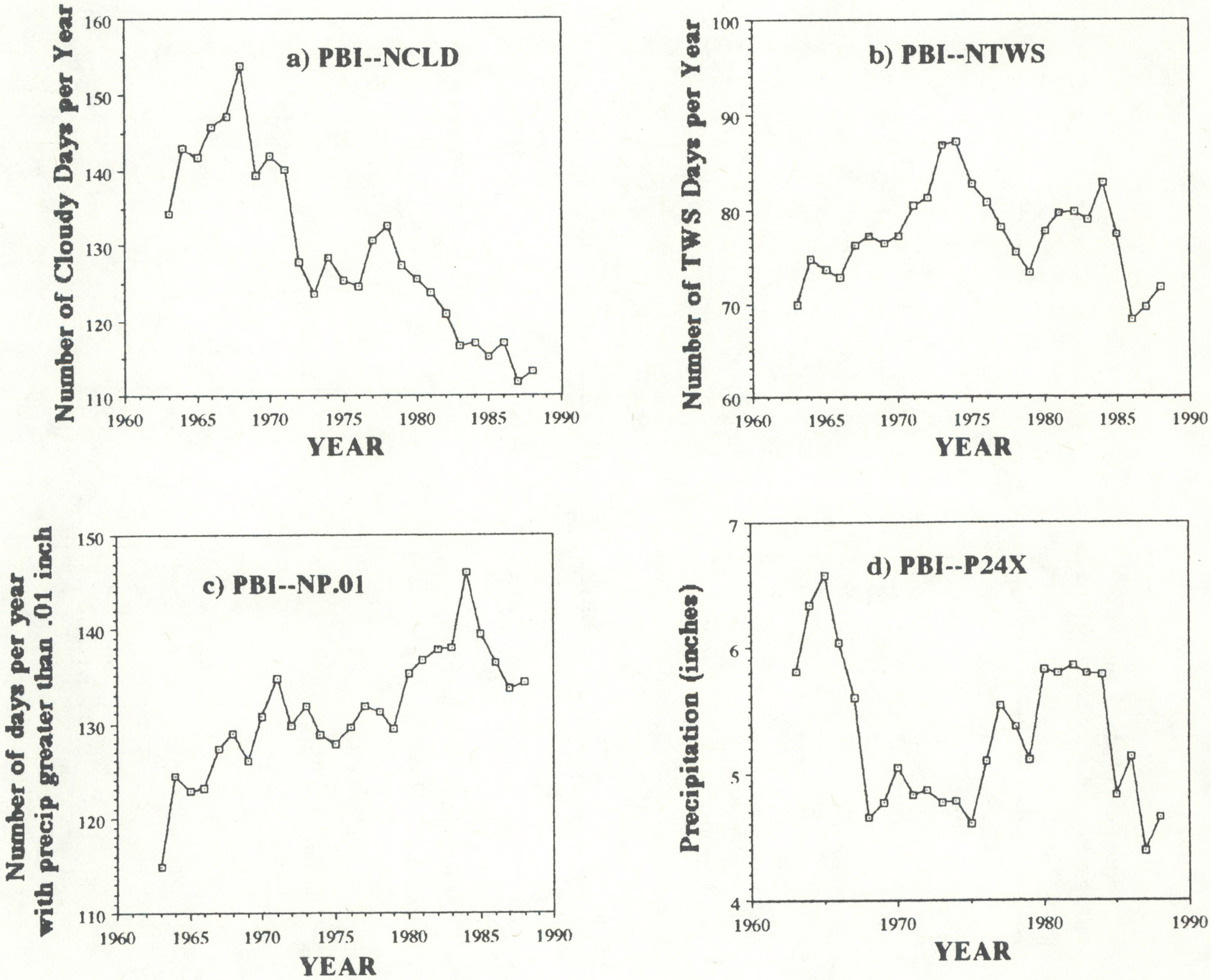

Figure 6. Five-year running means of PBI precipitation variables: (a) number of cloudy days per year (NCLD); (b) number of thunderstorm days per year (NTWS); (c) number of days per year with precipitation greater than .01 inches (NP.01); and (d) precipitation on day of year with greatest precipitation (P24X).

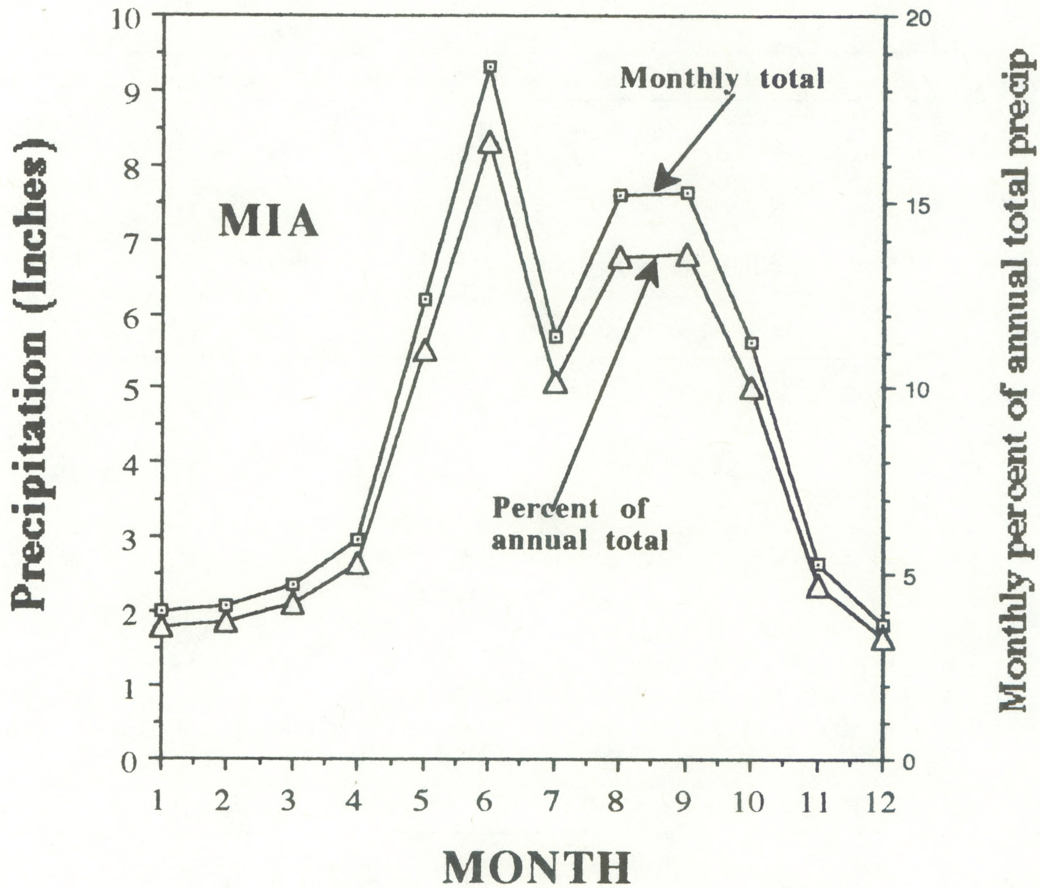

Figure 7. Miami annual variation of monthly mean (1961-1990) precipitation totals and of the fraction of the mean annual precipitation provided by each month.

Table 6. Spearman correlation coefficients between MIA and PBI annual precipitation variables (1961-1990). Asterisks denote statistical significance at the 99% level (***) and the 95% level (**). See text for definitions of variables.

Variable	Spearman Correlation Coefficient
NCLD	.78***
NTWS	.65***
NP.01	.67***
P24X	.36**

Table 7. Spearman correlation matrix for MIA annual precipitation variables (1961-1990). Asterisks denote statistical significance at the 99% level (***), the 95% level (**), and the 90% level (*). See text for definition of variables.

	Precipitation	NCLD	NTWS	NP.01	P24X
Precipitation	1.00	0.26	0.14	0.58***	0.73***
NCLD	0.26	1.00	-0.19	0.04	0.21
NTWS	0.14	-0.19	1.00	0.33*	-0.06
NP.01	0.58***	0.04	0.33*	1.00	0.18
P24X	0.73***	0.21	-0.06	0.18	1.00

Table 8. Spearman correlation matrix for PBI annual precipitation variables (1961-1990). Asterisks denote statistical significance at the 99% level (***), the 95% level (**), and the 90% level (*). See text for definition of variables.

	Precipitation	NCLD	NTWS	NP.01	P24X
Precipitation	1.00	0.33*	0.08	0.65***	0.50***
NCLD	0.33*	1.00	0.02	0.05	0.01
NTWS	0.08	0.02	1.00	0.36*	-0.17
NP.01	0.65***	0.05	0.36*	1.00	0.29
P24X	0.50***	0.01	-0.17	0.29	1.00

Table 9. Comparisons of MIA mean (1961-1990) precipitation between June and the months indicated in the first column. The third and fourth columns give the results of statistical tests to determine whether the June mean is significantly different from the means of the months indicated in the first column. Asterisks denote significance at the 99% level (***) and at the 90% level (*). The Wilcoxon signed-rank test (Ott, 1988) is a non-parametric version of the two group paired t-test (Abacus Concepts, 1987).

	Precipitation Difference (inches)	Student T-Test	Wilcoxon Signed-Rank Test
June-July	3.62	***	***
June-August	1.74	*	*
June-September	1.69	*	---
June-October	3.69	***	***

returns to the Florida-Cuba area during September-October. Alternatively, it has been suggested (Burpee, 1994) that the maxima in June and August-September are simply reflections of middle latitude frontal zones that impact south Florida precipitation in early summer, in late summer, and in early fall, but not in mid summer.[5]

The July precipitation minimum is associated with a minimum in tropical weather system activity. Table 4 shows that tropical weather systems in the vicinity of MIA during 1961-1990 have been far less frequent in July than in the other months of June-October. Of course, this could be a reflection of the position of Riehl's climatological upper level trough or of some other larger scale meteorological factor. Table 10 shows a systematic (although only statistically significant in June and July) relationship between monthly tropical weather system frequency and monthly precipitation.

Figure 8 is a year-month cross section of MIA monthly precipitation totals. We see that the peak of annual rainfall totals during the decade of the 1960's (Figure 2c) is the result of anomalously high rainfall in June and September-October. Table 11 shows the MIA June and October precipitation totals for 1964-1969 and their ranks (1-30) in the 30-year sample. Also shown is the tropical weather system activity for these months as a function of year. A direct relationship between precipitation and tropical weather system activity seems to hold in June but not in October. Table 11 leads one to feel that the concomitant variation of tropical weather system activity and precipitation, discussed above, is a consequence of the partial control of both of these events by larger scale meteorological processes and that these relationships can only be expected to hold in a very general sense. Figure 8 shows that the June and September-October maxima, as well as the mid-summer (July) rainfall minimum, persist through the 1970's and that the 1980's are characterized by complex and weaker precipitation features with a broad maximum from May-September. Even in the late 1980's, however, we can find a mid summer (July) precipitation minimum.

Table 12 shows the Spearman correlations between MIA monthly precipitation totals and NCLD, NTWS, NP.01, and P24X. The 12-month averages of these correlations give, qualitatively, the same results with regard to the rank order of the correlations as obtained from the annual averages (Table 7). In descending order, these are P24X, NP.01, NCLD, and NTWS. However, the correlations based on the monthly values are substantially higher than those based on annual data and most are statistically significant.

The correlations between P24X and monthly precipitation totals are extremely high with only the values for June-September falling below 0.90. The P24X correlations for all months are significant at the 99% level. Since the variable P24X represents the rainfall on only the single rainiest day of the indicated month for each year, the month-to-month consistency of this relationship, the magnitudes of these correlation coefficients, and the high degree of statistical significance are all very surprising. However, the fact that the correlations are smaller in the wet season is not surprising and is explained by Figure 9c which shows that the mean monthly value of P24X is about 50% of the mean monthly precipitation in the winter months and only about 30% of the mean monthly precipitation in the summer months. Figure 9b, in which the data have been normalized by subtracting the mean and dividing by the standard deviation, shows that the annual variations of the precipitation total and P24X are closely in phase. The correlations between precipitation and NP.01 are, on the average, the second largest (Table 12). Despite the fact that these correlations are well below the correlations with P24X, the values for all months except July are significant at the 99% level and the July correlation is significant at the 95% level.

The 30-year means of NCLD, NTWS, NP.01, and P24X, have rather simple intra annual variations with broad maxima during the warm season and relatively low values during the winter (see Figure 10). Figures 11a and 11b show, respectively, the 30-year maximum and minimum precipitation for each month of the year. We see that the months with the largest maximum precipitation are May (about 18 inches) and June (about 22 inches). These both occurred in 1968 and provided about half of that year's 83 inches

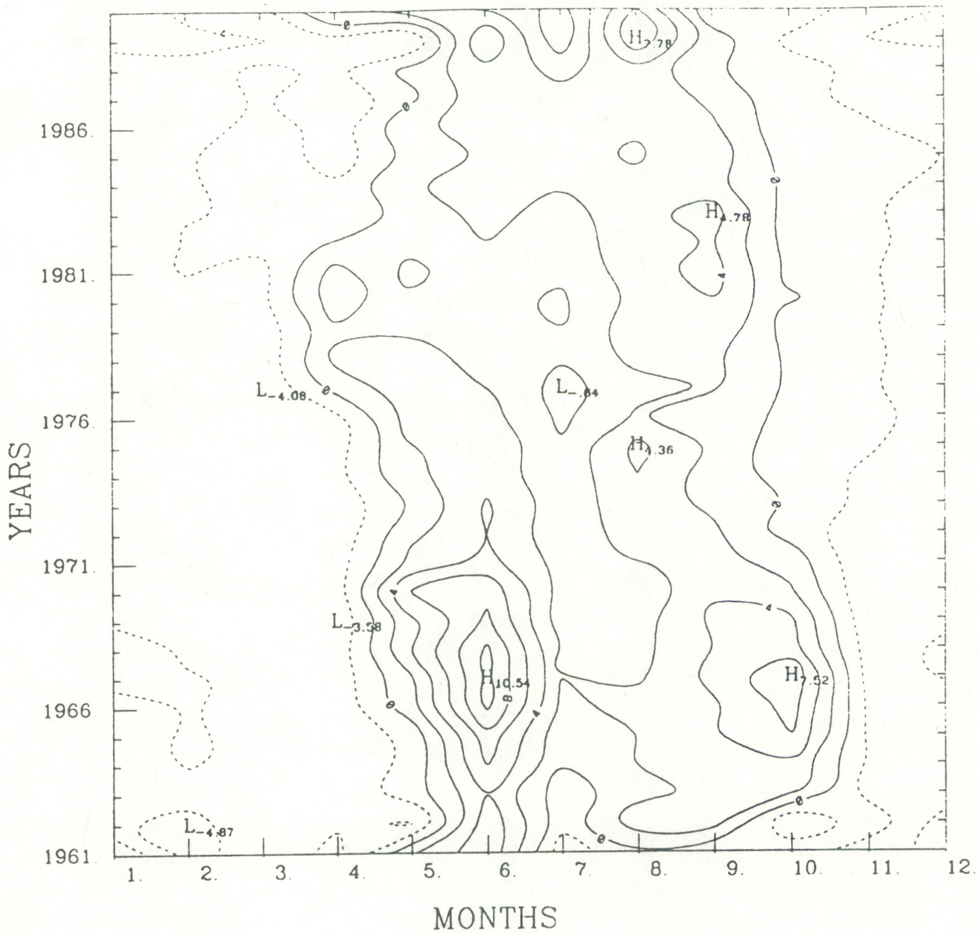

Figure 8. MIA year-month cross section of precipitation departure from 5 inches. Data for each month have been smoothed with five-year running averages. Contour interval is 2 inches. Contours for negative values are dashed.

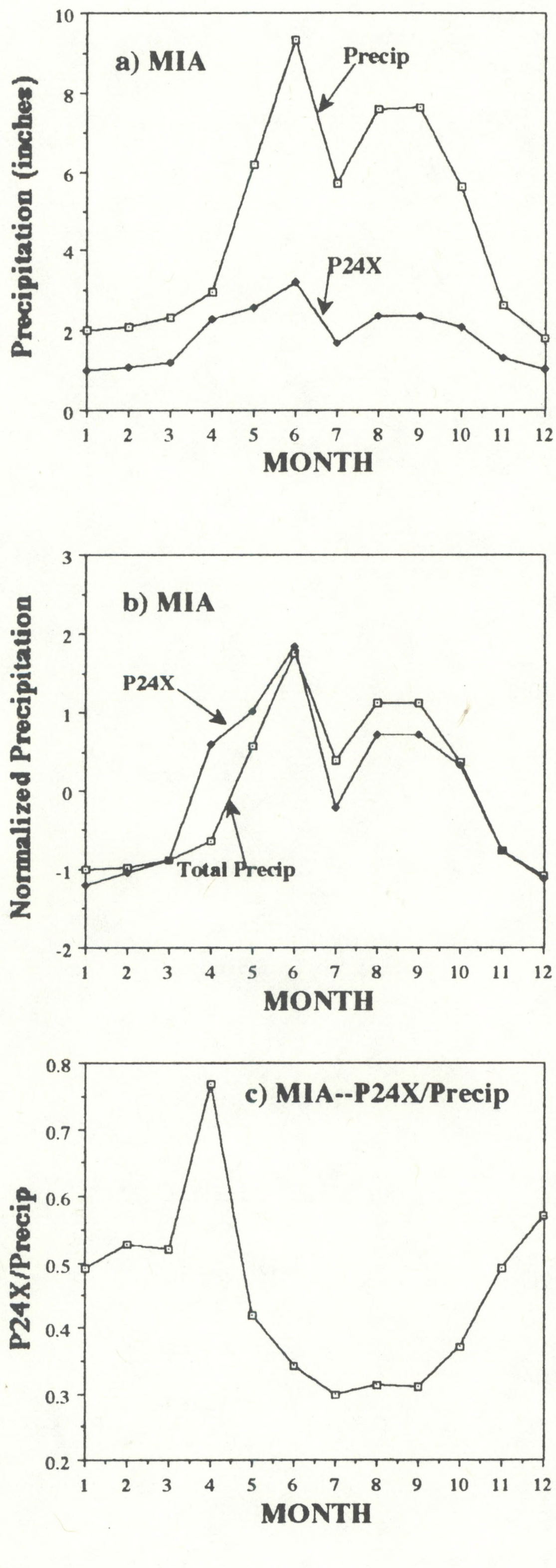

Figure 9. Relationships between 30-year means of monthly MIA precipitation and greatest precipitation in 24 hours (P24X) as a function of month: (a) in inches of precipitation; (b) normalized by subtracting mean and dividing by standard deviation; and (c) ratio of P24X to mean precipitation.

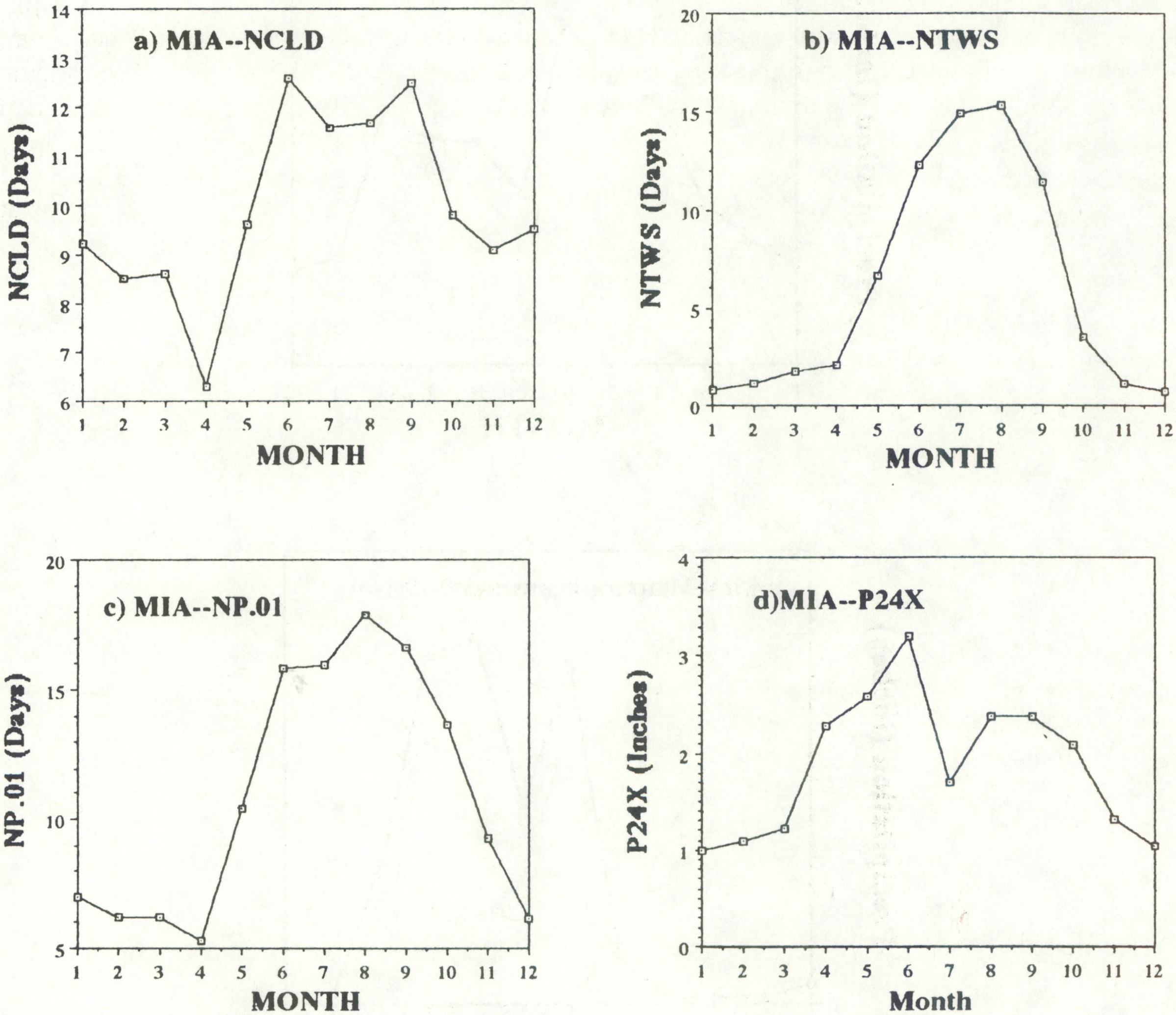

Figure 10. Intra annual variation of mean (1961-1990) monthly MIA precipitation variables. See text for definition of variables.

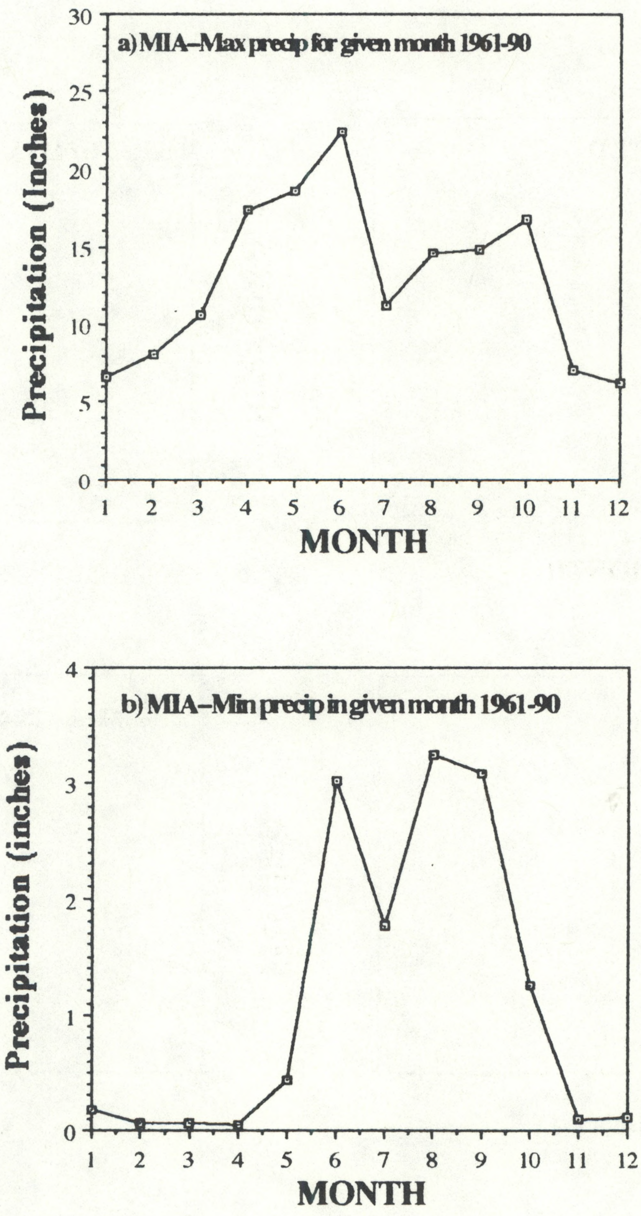

Figure 11. MIA precipitation variables: (a) maximum precipitation in month (1961-1990); and (b) same but for minimum precipitation.

Table 10. Intra monthly variation of: (1) number of years during 1961-1990 with tropical weather systems within 200 nautical miles of MIA; (2) number of years during 1961-1990 without tropical weather systems within 200 nautical miles of MIA; (3) average precipitation for years with tropical weather systems within 200 nautical miles of MIA; and (4) average precipitation for years without tropical weather systems within 200 nautical miles of MIA. In parentheses are probabilities from unpaired Student t-tests that the means of samples from populations with the same mean can differ by as much as columns (3) and (4).

Month	(1) Number of Years With Tropical Weather Systems	(2) Number of Years Without Tropical Weather Systems	(3) Average Precipitation for Years With Tropical Weather Systems (inches)	(4) Average Precipitation for Years Without Tropical Weather Systems (inches)
May	1	29	10.9	6.0 (p = .14)
June	6	24	12.9	8.4 (p = .01)
July	1	29	11.2	5.5 (p = .01)
August	11	19	7.9	7.4 (p = .33)
September	10	20	8.4	7.2 (p = .16)
October	7	23	6.9	5.3 (p = .17)

Table 11. June and October precipitation totals (1964-1969) and 30-year (1961-1990) ranks for each June and October. Tropical weather system activity indicated in parentheses following rank.

Year	June Precipitation (inches)	June Rank	October Precipitation (inches)	October Rank
1964	10.5	9	9.8	5 (Isabel)
1965	6.6	22	16.8	1
1966	21.4	2 (Alma)	10.9	4
1967	16.0	3	12.9	3
1968	22.4	1 (Abby, Brenda)	8.7	6 (Gladys)
1969	11.4	6	13.4	2 (Jenny)
Avg.	14.7	7.3 (4.2)*	12.1	3.5

*Value in parentheses is average obtained when 1965 is omitted.

Table 12. Spearman correlation coefficients between MIA precipitation and the variables shown by the table headings for each month of the year (1961-1990). Asterisks denote statistical significance at the 99% level (***), the 95% level (**), and the 90% level (*).

Month	NCLD	NTWS	NP.01	P24X
January	.55***	.35*	.74***	.92***
February	.65***	.41**	.57***	.92***
March	.12	.54***	.60***	.89***
April	.40**	.74***	.82***	.94***
May	.55***	.61***	.70***	.92***
June	.64***	.34*	.53***	.72***
July	.43**	.40**	.45**	.68***
August	.41**	.43**	.68***	.81***
September	.69***	.24	.60***	.87***
October	.72***	.46**	.49***	.93***
November	.34*	.10	.54***	.94***
December	.34*	.60***	.60***	.91***
Avg.	.49	.39	.61	.87

of rain (see Table 1). As a result, 1968's rainfall exceeded the 30-year annual mean by 2.5 standard deviations. It is noted that in June 1968, two tropical weather systems, Abby and Brenda, passed within 200 nautical miles of MIA. After May and June of 1968, the next largest rainfall in a single month during 1961-1990 was about 17 inches in April 1979. Figure 11b shows that the winter dry months, January-April and November and December, have had years where the precipitation was as little as 0.1-0.3 inches.

PBI's mean (1961-1990) annual precipitation total (see Table 2) is 60.7 inches. When divided by 12, the mean annual monthly precipitation at PBI is found to be 5.06 inches. From Figure 12, the months May-October at PBI, like MIA, are seen to have precipitation in excess of the annual monthly mean and, also like MIA, the months November-April have average precipitation that is less than the annual average. The six rainy season months at PBI contribute 42 inches of the mean annual precipitation which is identical to the amount found for MIA. Figure 12 shows a double peak in the summer rainfall at PBI similar to that discussed earlier for MIA (see Figure 7) and Table 13 shows the results of statistical tests for the significance of PBI precipitation differences between summer months analogous to those shown by Table 9 for MIA.

From Figure 13 we see that the annual rainfall maximum for PBI in the 1960's (Figure 2c) is also the result of high rainfall in June and September-October. These features, as well as the mid summer (July-August) minimum, persist through the 1970's. Similar to MIA, the 1980's are characterized by complex and weaker precipitation features. Although July and August have slightly less precipitation than June and September, the essential feature of the summer months in the 1980's is a broad maximum from June through September.

5. SUMMARY

Rainfall data for the period 1961-1990 at MIA and PBI were studied. The official rain gauges at MIA and PBI were moved, respectively, 9,200 ft and 4,750 ft on 1 March 1977. However, three statistical tests failed to reveal inhomogeneities in the time series of annual precipitation totals (1961-1990) that might have resulted from these rain-gauge relocations.

Although MIA and PBI are separated by approximately 75 miles, and despite the fact that the mean annual rainfall at PBI is 4.6 inches greater than at MIA, the low frequency components of the mean annual precipitation totals at these two stations (as illustrated by smoothing through computation of five-year running means) are closely in phase and have distinct decadal-scale fluctuations. The mean annual precipitation for both the decades of the 1960's and the 1980's exceed that of the 1970's. A fluctuation of tropical weather system activity, such that tropical weather systems passing within 200 nautical miles of MIA in the 1960's and 1980's were more frequent than was the case for the 1970's, was found which is statistically significant at the 95% level. Further analyses revealed that MIA precipitation was systematically related to tropical weather system frequency on monthly and seasonal time scales but not so precisely that one could conclude a cause and effect relationship existed.

Spectral analysis revealed the annual precipitation totals at MIA and PBI had well marked peaks at a period of 15 years and that both stations also showed considerable spectral intensity at a period of 10 years. In addition, PBI showed a second peak at 4.28-5.0 years whose difference from the MIA spectral intensity at the five-year period was statistically significant at the 95% level. Since an El Niño signal would be expected to have similar impacts on both MIA and PBI, the secondary peak at PBI does not appear to be an El Niño effect. Cospectral calculations indicated that the correlation between annual precipitation totals at MIA and PBI was primarily due to fluctuations with periods of 10 years or more.

Spearman correlation coefficients were calculated between the two stations for the annual values of NCLD, NTWS, NP.01 and P24X. Although the highest correlation (0.78) was found for NCLD, the corre-

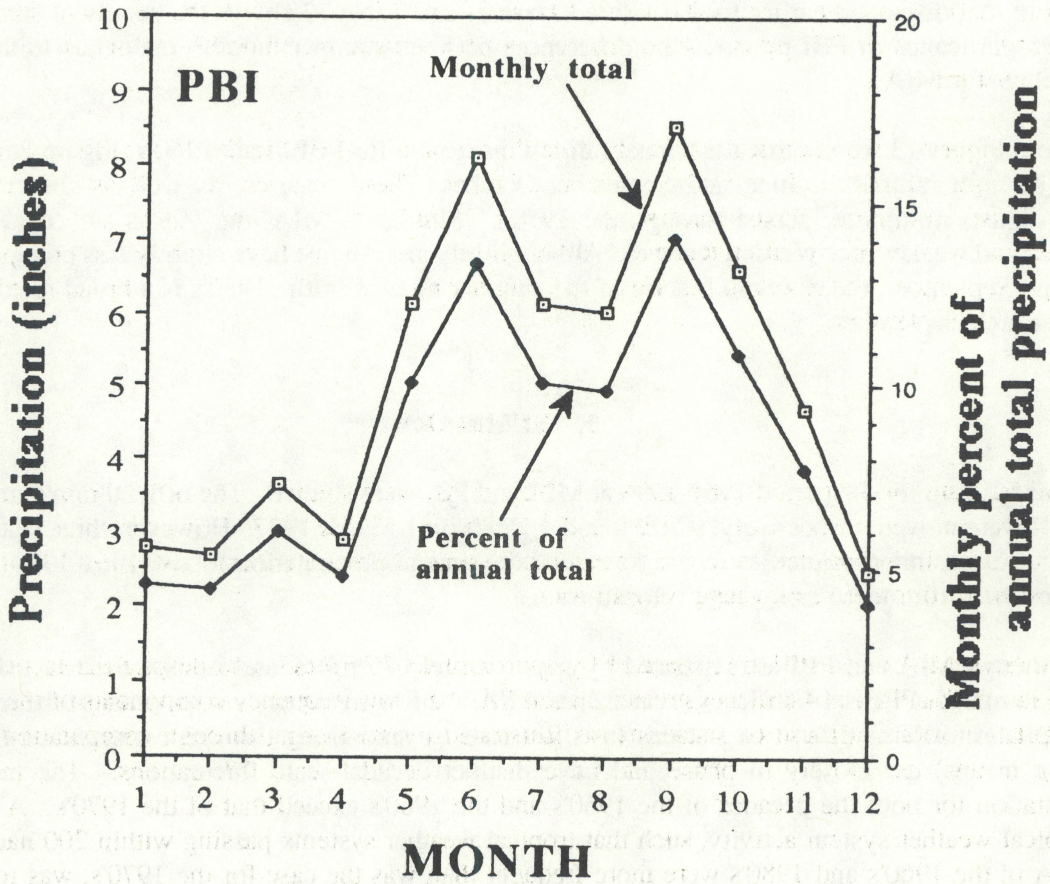

Figure 12. PBI annual variation of monthly mean (1961-1990) precipitation totals and of the fraction of the mean annual precipitation provided by each month.

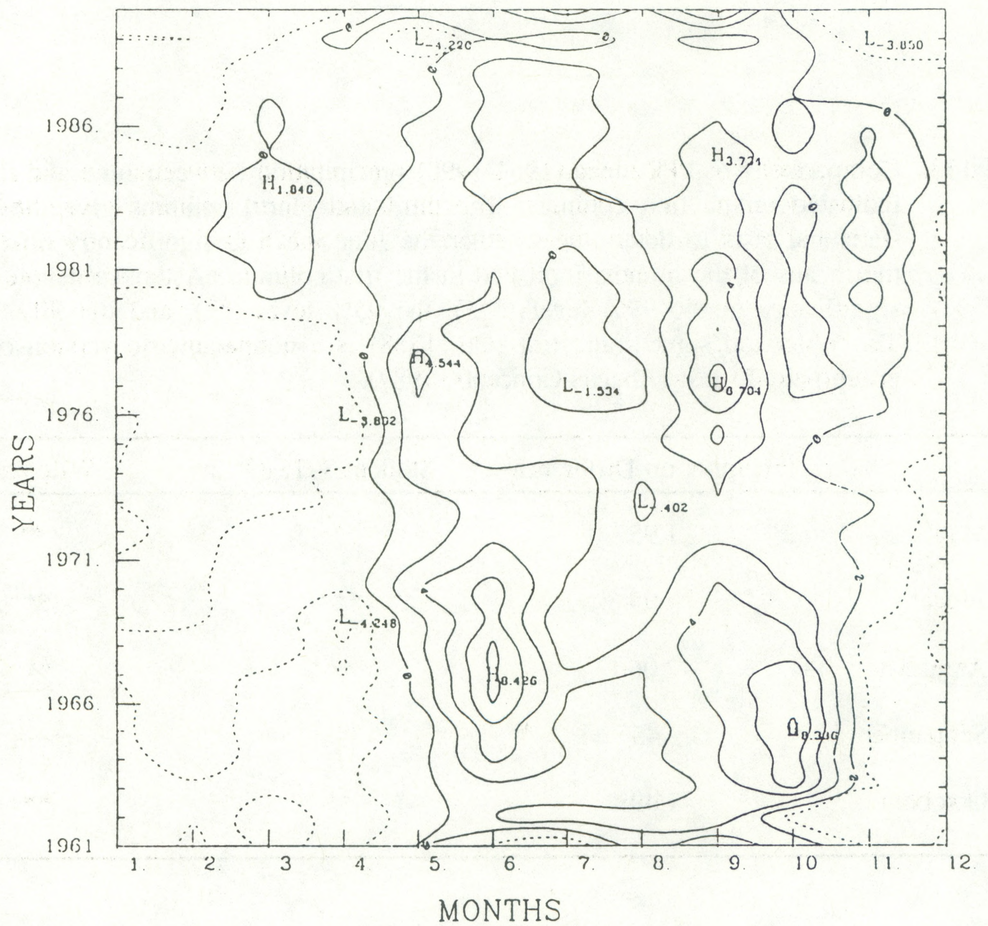

Figure 13. PBI year-month cross section of precipitation departure from 5 inches. Data for each month have been smoothed with five-year running averages. Contour interval is 2 inches. Contours for negative values are dashed.

Table 13. Comparisons of PBI mean (1961-1990) precipitation between June and the months indicated in the first column. The third and fourth columns give the results of statistical tests to determine whether the June mean is significantly different from the means of the months indicated in the first column. Asterisks denote statistical significance at the 99% level (***), the 95% level (**), and the 90% level (*). The Wilcoxon signed-rank test (Ott, 1988) is a nonparametric version of the two group paired t-test (Abacus Concepts, 1987).

	Precipitation Difference	Student T-Test	Wilcoxon
June-May	1.95	**	***
June-July	1.94	**	**
June-August	2.06	***	**
June-September	-.45	---	---
June-October	1.49	*	**

lations for NCLD, NTWS, and NP.01 were all significant at the 99% level and that for P24X was significant at the 95% level (Table 5). When Spearman correlation matrices were formed between annual precipitation totals, NCLD, NTWS, NP.01, and P24X separately for each of the two stations (Tables 7 and 8), the only correlations that were significant at the 95% level were those between precipitation totals and NP.01 and P24X. The time series of NCLD at both stations showed statistically significant (99%) negative trends. In contrast, NP.01 has a statistically significant (95%) positive trend at PBI and a small positive trend at MIA which indicates that the number of cloudy days per year at these stations decreased during 1961-1990 while the number of days with measurable precipitation increased.

This lack of consistency between the annual values of NCLD and NP.01 led to an examination of data for individual months. At both stations the monthly mean precipitation totals exceeded the mean annual monthly precipitation from May-October and the reverse was true for November-April. The rainy season months (May-October) contribute 42 inches to the annual rainfall total at both stations.

Year-month cross sections of both MIA and PBI monthly precipitation totals (Figures 8 and 13) showed that the peak annual rainfall total during the decade of the 1960's (see Figure 2c) was the result of anomalously high rainfall in June and September-October during the later half of the 1960's. The June precipitation maximum is present in all three decades of the 1961-1990 sample but is the primary maximum only in the 1960's.

Spearman correlations with precipitation and each of the variables, NCLD, NTWS, NP.01, and P24X, were run using monthly data from MIA. It was found (Table 12) that the annual averages of the monthly correlations were, in descending rank order, P24X, NP.01, NCLD, and NTWS. In particular, the correlations between monthly P24X and monthly precipitation totals were found to be extremely high with only the values for June-September falling below 0.90. The P24X correlations for all months are significant at the 99% level. Since the monthly values of P24X represent the rainfall on only the single rainiest day of the indicated month for each year, the month-to-month consistency of this relationship, the magnitudes of the correlation coefficients, and the high degree of statistical significance are all very surprising.

6. FOOTNOTES

[1]The data are taken from standard NOAA publications (U.S. Dept. Comm., 1961-1990a,b). Since these publications provide data in English units, the latter are used throughout this report.

[2]The fifth session of the Intergovernmental Panel on Climate Change (IPCC) adopted six tasks for the ongoing work of its working groups (Houghton *et al.*, 1992) that included, "Predictions of the regional distributions of climate change and associate impact studies..." The World Meteorological Organization (WMO, 1966) has encouraged compilation and analysis of regional climatic data for relatively short (even as short as 10 years) periods of the recent record and has urged that the temporal fluctuations contained in these records be searched for statistical evidence of non-randomness.

[3]Because frequency distributions of precipitation generally do not approximate the normal distribution, the primary measure of association used in this paper is the nonparametric Spearman correlation coefficient (Ott, 1988).

[4]The monthly totals have not been adjusted for differences in the lengths of months.

[5]Bezdek (1994) reports that a double sea-level pressure minimum is found in the Caribbean and Central American regions that could possibly be associated with the double warm-season precipitation maximum described above.

7. ACKNOWLEDGMENTS

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8. APPENDIX: STATISTICAL CONSIDERATIONS

(a) Effective Sample Size

Since successive values of climatological data are usually positively correlated, a time series of n values has effectively less information than would be the case in a random sample of n values (WMO, 1966). This, in turn, reduces the significance obtained from common statistical tests below that which would be obtained if successive observations were independent. Siegel (1956) developed an objective method for estimating the effective independent sample size from a serially correlated time series. When applied to the MIA and PBI annual precipitation totals, Siegal's method gives 22 independent values for the former and 34 independent values for the latter.

(b) Student T-Tests

For a one-tailed Student t-test, the t-values critical at the 5% level are for 30, 15, and 10 degrees of freedom, respectively, 1.70, 1.75, and 1.81. With 30 degrees of freedom, only a 6% change of the computed slope would also change the t-value from 1.70 to 1.81. In the data sets used here, therefore, the critical t-values do not appear to be overly sensitive to the serial correlation in the data. From a qualitative point of view, persistence can be ignored in these tests. It is noted that these tests work well in the absence of normality (WMO, 1966).

(c) Spearman Rank Correlation Coefficient

This coefficient is a correlation based on the ranks of the two variables being compared (Abacus Concepts, 1987; Ott, 1988). The corresponding test of significance is nonparametric. Serial correlation was ignored in these tests.

(d) Mann-Kendall Rank Statistic

This statistic allows us to test randomness in the time series against the alternative of trend (WMO, 1966). The trend can be linear or nonlinear. This is a nonparametric test. Serial correlation was ignored in these tests.

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