RECENT CLIMATIC FLUCTUATION ON A SMALL TROPICAL ISLAND: THE CASE OF BARBADOS, WEST INDIES

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RECENT CLIMATIC FLUCTUATION ON A SMALL TROPICAL ISLAND: THE CASE OF BARBADOS, WEST INDIES

BY

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"The Earth's climate has undergone many changes in the past, and changes of a similar nature may be expected to occur in the future. Although the broad characteristics of the global climate have remained fairly stable and stationary since the end of the last glacial epoch some 10,000 years ago, climatological records based on the synthesis and statistical averaging of daily weather records of temperature, rainfall, etc. show considerable variations from year to year, from decade to decade and from century to century...."

B.J. Mason
(Endeavour XXXV, 1976, p. 51)

For Marcia, my wife

ABSTRACT

Climate is nowhere invariant, it is ever changing. For many decades now climatologists have recognized this and have attempted to analyse and explain the magnitude, direction and spatial extent of such change. At the same time scientists have postulated several theories to account for known fluctuations and altogether a very extensive literature has been built up around the subject. Yet, there seems to be a relative dearth of detailed investigations of low-latitude climatic fluctuations; for the most part researchers in the past have tended to concentrate on analyses involving the middle and high latitudes. The present work, therefore, is offered as a contribution to a better understanding of climatic variation in a vastly neglected low-latitude region, the Caribbean.

This study attempts to assess the magnitude and direction of recent climatic fluctuations on the island of Barbados. More specifically, it sets out primarily to identify long-term fluctuations and trends in the island's climatic data, as they may exist, since 1900. Throughout the analysis an attempt is made, wherever possible, to compare and relate these fluctuations and trends to postulated global and hemispheric changes and to other low-latitude climatic flucuations and atmospheric circulation changes which have been recently observed.

Chapter 1 provides a general introduction to the study area and focuses primarily on relevant background information relating to the island's climate.

In Chapter 2 a comprehensive outline of the main types of data, data sources and methodological procedures is given. Here, particular emphasis is placed on the main statistical techniques employed in the analysis.

The following Chapter is devoted to a full investigation of long-term fluctuations and trends identified for selected climatic parameters. These variables include air temperature, atmospheric pressure, wind velocity, sunshine hours, relative humidity and cloud cover. In the final part of this Chapter there is a brief discussion of the relative merits of a few theories of climatic change.

In the fourth Chapter there is a detailed analysis of rainfall fluctuations across the island. This involves a thorough investigation of temporal variations in the island mean rainfall and also an analysis of the temporal and spatial patterns exhibited by seven selected rainfall stations. Partial explanations for these fluctuations are posited and an attempt is made to relate these patterns to observed hemispheric and tropical atmospheric circulation changes.

Chapter 5 deals exclusively with fluctuations and changes in the frequency of the major synoptic scale systems which affect the island's weather. These systems include hurricanes, tropical storms and depressions and local convectional (thunder) storms. In this Chapter there is also an attempt to examine the relationships between rainfall and these weather systems.

Finally, Chapter 6 is a concise summary of some of the major findings and results previously discussed; a very brief evaluation of the work is also given.

ACKNOWLEDGEMENTS

A number of people have given valuable assistance both in the initial data collection and in the final preparation of this thesis. To all of these people I express sincere thanks.

It is impossible to single out for special mention, the name of every individual who contributed in some way towards the completion of this work. However, at the risk of being partial, I want to express thanks to my advisor, Dr. Colin E. Banfield of the Geography Department, Memorial University, who was always willing to make worthwhile suggestions and comments.

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Finally I also want to express gratitude to Mr. Roger Cutting who helped to tabulate the original data and to Miss Judith Drake who kindly consented to type the final script.

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Chapter 1

Background to the Island's Climate

A. Introduction

The island of Barbados is the most easterly of the Caribbean archipelago and is situated at approximately latitude 13° 14'N and longitude 59° 37'W. The island, which is about 33.5 km. long and 22.5 km. wide, covers a mere 430 sq. km. For the most part Barbados is flat and low-lying with its highest point, Mount Hillaby, reaching just over 335 metres (see frontispiece).

The climate of Barbados is to a large extent determined by three main factors, namely solar radiation, sea surface temperatures and air flow characteristics and patterns. Owing to the island's location relative to the seasonal movement of the sun north and south of the equator, there is an almost constant receipt of solar radiation at the surface all year round. At the same time the island is located in the tropical North Atlantic ocean whose surface temperature, about 26.7°C. hardly shows any substantial annual or monthly variation.[1] Thirdly, like all other regions in the Caribbean, Barbados lies within the Northern Hemisphère Tropical Easterlies or Trade Wind belt, a circulatory system associated with the semi-permanent high pressure zone centred just to the south of Bermuda and the Azores. It is generally regarded as a regular, fairly persistent type of circulation. Hence, the island is generally under the influence of a relatively constant easterly flow of warm, fairly moist air.

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[1] Rocheford, B.A., Paper Presented to the Eleventh Caribbean Food Crops Society Conference, Bridgetown, Barbados, 1973, p. 4.

Broadly, the climate may be divided into a wet season and a dry season; the wet season lasts from about June to November, associated with a northward shift of the Intertropical Convergence Zone (ITCZ), while the dry season extends from December to late May or June. It should be pointed out, however, that it is not uncommon for there to be dry spells during the wet season and wet spells during the dry season. Two other seasonal divisions have been proposed; a cool season and a warm season, corresponding roughly with the months December to March and April through November, respectively.[2] But these latter seasonal divisions are not unvarying; a look at the statistics of the island's recent climatic past would show that very often the so-called cool season may be of a longer duration, while the length of the 'normal' warm season may contract.

B. Air Temperature

It is a known fact that the air temperature over Barbados is largely determined by the temperature of the northeast trades which blow constantly from over the warm North Atlantic ocean. Since, as already pointed out, there is little variation in sea surface temperature throughout the year, it is not surprising that there is little diurnal or annual variation in air temperature over the island. Similarly, because of the relatively flat nature of the island, air temperatures recorded show very little spatial variation. At the same time the island is very small and hence no point is too far inland to escape the influence of the winds blowing from over the surrounding ocean. However, it has been suggested that temperatures in the 'highland' areas (generally above 300 metres) may be about

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[2] Skeete, C.C., An Historical Description of the Weather of the Island of Barbados West Indies - 1901 to 1960, Barbados Gov't. Printing Office, 1963.

2-3°C below that recorded in lowland and coastal regions.[3]

Usually, temperatures seldom exceed 33°C or fall below 16°C. In fact, temperature data for the island for the period 1903-1975 show that there was a mean annual temperature of 26.3°C. Figure 1 shows the annual variation about this mean. Over the same period the highest and lowest mean monthly temperatures were recorded in the months of August and February, respectively. The mean for August for the 73-year period was 27.0°C, while it was 24.9°C for February, thereby giving a mean range of only 2.1°C between the warmest and coolest months.

To further confirm that there is no significant annual variation in the island's temperature statistic, the standard deviation (σ) and coefficient of variation (V) of mean annual temperature were calculated. These measures of central tendency can serve as reasonable indices of variability and dispersion in any data set. In the case of the Barbados data, the values for the standard deviation and coefficient of variation were +0.61 and 2.3%, respectively.

As mentioned elsewhere, temperatures tend to be lowest during the period December to March. The reduction in temperature at this time of the year is the result of, and coincides with, the movement of the sun south of the equator (with reduced angle in the sky) and the associated reduction in sea surface temperature. Constrastingly, air temperatures are normally highest during May - August when there is maximum receipt of solar radiation at the latitude of Barbados. During the height of the wet season, however, a slight decrease in temperature is normally recorded; this is attributable partly to increased cloud cover which reduces the

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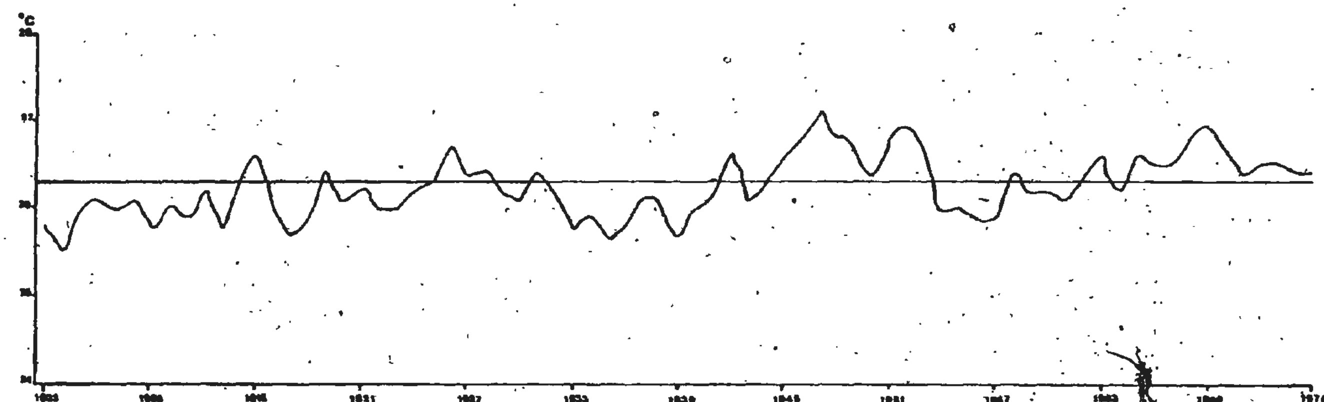
[3]Skeete, op. cit., p.8.

FIG. 1

BARBADOS MEAN ANNUAL TEMPERATURE FLUCTUATIONS



DATA SOURCE: METEOROLOGICAL OFFICE, SEAWELL

receipt of incoming, short-wave radiation at the surface, and partly to a loss of heat used up in evaporating part of the rainfall. As a result whenever there are prolonged dry spells during the normal wet season, almost invariably there is an increase in air temperature.

C. Sunshine

No sunshine data were taken at Barbados before the year 1929, and the reliable record of the parameter only extends as far back as 1937. Like atmospheric temperature, sunshine duration is relatively constant from month to month and hardly exhibits any spatial variation over the island. Perhaps the only exceptions are the months of September, October and November when there tends to be a slight reduction in sunshine hours.

Over the period 1937 to 1975, figures for the island show that the mean daily sunshine duration was approximately 8.4 hours. A further examination of the data reveals that the months of April and October experienced the greatest and least number of hours of mean daily sunshine, respectively. For the 39-year period which the record covers, April had a mean of approximately 8.9, whereas October recorded a mean daily figure of 7.7 sunshine hours: in other words, the difference in mean daily sunshine hours between the two months is only 1.2 hours. At the same time it should also be pointed out that the greatest and least number of mean daily hours of sunshine duration recorded were 10.3 hours (May 1941) and 4.6 hours (Nov. 1939), respectively.

It may be of some interest to note that the months of highest and lowest number of sunshine hours show a slight positive relationship with the dry and wet seasons, respectively. As the rainy season advances with its associated increase in cloud cover, there tends to be a fairly predictable decrease in the number of sunshine hours recorded. As might also be expected, the months with the greatest and least number of sunshine hours tend to coincide (at least approximately) with the "warm" and "cool" seasons.

It appears that at the latitude of Barbados, elevation has a negligible effect on sunshine duration. In 1929 a sunshine recorder was set up at Lion Castle, a highland station at 274.6m elevation. It was found that there was no significant difference between the number of sunshine hours recorded there and that recorded at Seawell and Codrington.[4] The results of this experiment appear reliable since similar findings have been reported from the neighbouring island of Jamaica to the northwest.[5]

D. Cloud Cover

Convectional type clouds tend to predominate over the island of Barbados. There are several variations of these clouds which range from the relatively small and shallow *cumulus humilis* to the great *cumulus congestus* and *cumulonimbus*. Generally, cumulonimbus and cumulus congestus are more frequently seen during the months of July to October and therefore show rough correspondence with the wet season. On the other hand, the smaller cumulus humilis type tends to be a fairly common sight during the normal dry season. It must be emphasized, however, that these are merely general tendencies observed over a period of years.

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[4]Personal communication with C.C. Skeete, former Director of Agriculture, Ministry of Agriculture, Lands and Fisheries.

[5]See The Climate of Jamaica - First edition prepared by the Climatology Branch of the Jamaican Meteorological Service, 1973, p. 62.

Although the island is small, it is often possible to find variations in amount of cloud from point to point. For instance, data for the former climatological station at Codrington, St. Michael, reveal that over the period 1931 to 1958, the monthly mean cloud amount was 5.4 oktas, ranging from a high of 7.0 oktas in 1950 to a low of 3.6 oktas in the year 1942. Data from the National Meteorological Office at Seawell, Christ Church, on the other hand, show a mean of 3.6 oktas, with the highest and lowest mean amounts being 5.5 and 2.8 oktas in 1972 and 1949, respectively. Figure 2 portrays the mean annual cloud amount of the two stations.

The slight difference in cloud amount recorded at these two stations can perhaps be attributed to differences in location and topoclimatic factors. Codrington 57.9 metres above-sea-level, is located at approximately latitude 13° 08'N, longitude 59° 36'W, while Seawell is situated at latitude 13° 04'N, longitude 59° 30'W and is very near to the southeast coast. Wind speed could also be an important factor. On the average, wind speeds are lower at Codrington than at Seawell; hence, these reduced velocities might easily favour a more rapid build up and formation of cloud at Codrington.

It has been observed that cloud amounts over Barbados are almost always highest during the day and lowest at night, especially between 8 p.m. and 2 a.m. As a general rule clouds also tend to build up more easily over the areas of higher elevation.[6] At the same time, it has been found that clouds over the island often build up in 'cloud streets' and tend to

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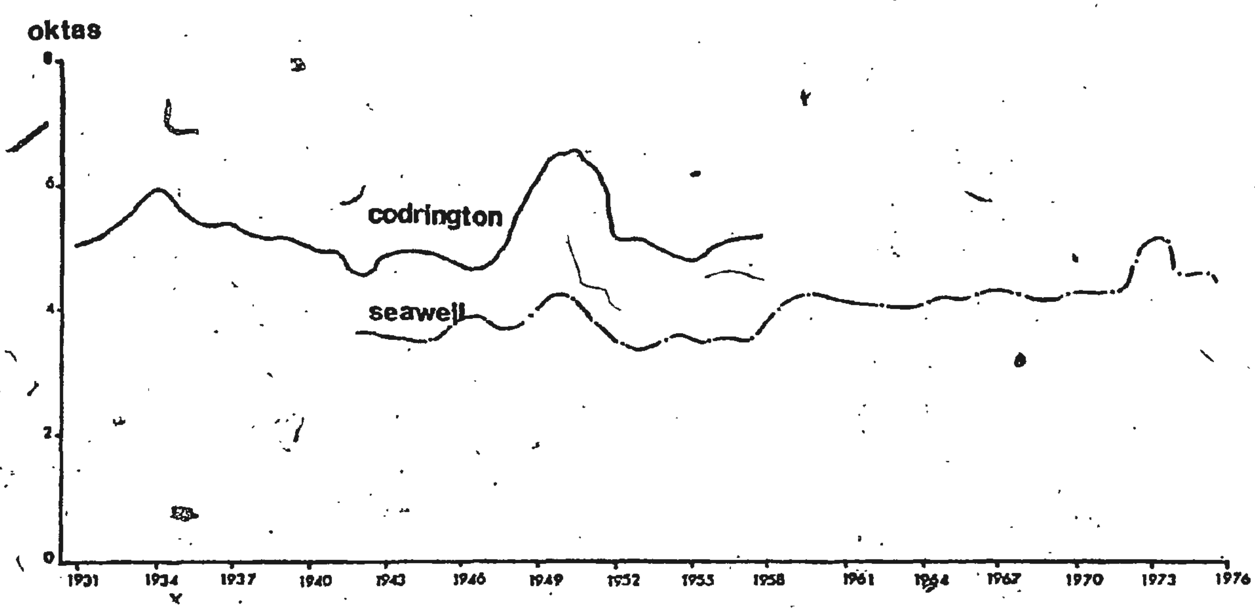
[6]See, for instance, Rocheford, *op. cit.*, p. 6

FIG. 2

FLUCTUATIONS IN MEAN ANNUAL CLOUD AMOUNT AT CODRINGTON AND SEAWELL



DATA SOURCE: METEOROLOGICAL OFFICE, SEAWELL

align themselves with the prevailing wind. This apparently is a feature of cumulus development in tropical areas, but so far no satisfactory explanation has been advanced. It is speculated that this phenomenon may be related to the *boundary layer structure* of the cloud and to wind speed.[7]

E. Wind

Since Barbados is situated within the belt of the Tropical Easterlies it is most frequently under the influence of winds blowing from directions between east and east-north-east. However, there are occasions when the winds blow from other directions for short periods. For example, during April and May the direction often shifts to east-south-east, whereas during August to November, especially with the approach of sporadic easterly waves, the predominant direction could be south-south-east or south. Again, it may be safely stated that air flow is hardly south westerely, westerly or north westerly; the only occasions on which wind currents blow from these directions are during the passage of cyclonic disturbances.

For the most part wind speeds are highest during the months of January to July and lowest from August to December. This pattern is apparently characteristic of the whole island. This is borne out by analysis of the data from the climatological stations at Codrington and Seawell. For instance, wind records from Seawell show that over the 34-year period (1942-1975) the months January to July had a mean wind speed of approximately 5.0 ms^{-1} while a mean of 4.0 ms^{-1} was recorded during the months of August through December. Similarly, the means for Codrington (1903-1962) were

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[7] Barry, R.G. and Chorley, R.J., Atmosphere, Weather and Climate, 3rd edition, Methuen, 1976, p. 282.

around 4.8 ms^{-1} and 3.6 ms^{-1}, respectively.

On occasions during the year, the trades may slacken considerably and light variable winds, sometimes virtual calms, may be experienced. This occurs rather infrequently however; for usually mean daily wind velocities hardly drop below 2.5 ms^{-1} or exceed 10 ms^{-1}. It is important to point out, though, that when the island's weather is being affected by easterly waves, tropical depressions or other synoptic scale systems, short gusts normally between 13-20 ms^{-1}, can be recorded. It is estimated for instance, that during the passage of hurricane 'Janet' in September 1955, wind velocities exceeding 50 ms^{-1} were recorded, before the anemometers at Seawell and Codrington failed.

F. Atmospheric Pressure

Pressure of the atmosphere over Barbados tends to assume much the same temporal pattern as the wind regime. The data suggest positive correlation between periods of higher wind speeds and higher air pressure and lower wind speeds and reduced air pressure (except with the passage of tropical storms and hurricanes). The pressure recorded clearly reveals that on average, higher pressure values persist during the first seven months of the year but show a slight decrease from August to December.

For example, the island mean air pressure for the period 1903-1975 (at mean sea level) during the months January to July was 1013.6 millibars, whereas it dropped to 1012.0 millibars for the months of August to December. The highest and lowest mean monthly values of pressure were recorded in the months of July and November, with 1014.1 and 1011.1 millibars, respectively. Generally, the months of reduced atmospheric pressure usually coincide roughly with the wet season and also with the normal 'hurricane season' when incipient storms and cyclonic disturbances affect the island's weather.

For the most part the air pressure at Barbados seldom exceeds 1014.5 millibars or falls below 1008 millibars. In fact, the island mean over the 73-year period was approximately 1013.0 millibars which is not significantly different from the January to July mean. However, when tropical depressions, storms or hurricanes pass close by or directly over the island, air pressure might plunge to as low as 988.0 millibars.[8] It seems fairly evident therefore, that since annual pressure fluctuations are to a large degree attributable to the influence of synoptic scale disturbances, the degree of fluctuation will vary annually.

G. Relative Humidity

As might be expected, mean relative humidity values are relatively constant throughout the year, but mean monthly values tend to increase during the months June through December. Conversely, monthly mean values of relative humidity show a slight but noticeable decrease during the first half of the year. These periods of high and reduced mean humidity values correspond closely with the already defined wet and dry seasons; hence, it is not surprising to find that the island exhibits this sort of pattern in its humidity regime.

Mean relative humidity data for Codrington and Seawell stations show that over the period of record, there was a mean annual value of 70% and

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[8] Skeete (1963) reports that during the passage of hurricane Janet the pressure dropped to a low of 990.5 mbs.

76%, respectively.[9] The mean monthly relative humidity for the months January to May at Codrington was only 68% but increased to 73% from June to December. Similarly, at Seawell, the January to May mean was 70%, whereas a mean value of 78% was recorded for the other months of the year. It might be noted that although the annual regimes are similar, the mean values of relative humidity are about 3% higher at Seawell than at Codrington. It has already been pointed out that Codrington is a relatively low-lying station about 3 kilometres or so inland from the coast; because of this there is a slight reduction in moisture content of the air at that station.

Humidity is a climatic parameter which is known to be highly temperature-dependent; usually other variables held constant, the warmer the air, the greater its moisture content. For this reason, mean annual air temperature and mean annual relative humidity values for the two stations were correlated statistically. In the case of the Codrington data the correlation coefficient (r) was +0.65 whereas a slightly higher coefficient +0.68 was calculated from the Seawell data. When the Student't t test' was applied, these values were found to be significant at the .01% level. By extension, it might be concluded that given the annual regimes exhibited in the various climatic parameters discussed above, one could also expect relatively high correlation between humidity and wind and air pressure. Fig. 3 gives some idea of the relationship between mean humidity and pressure fluctuations for Seawell and Codrington.

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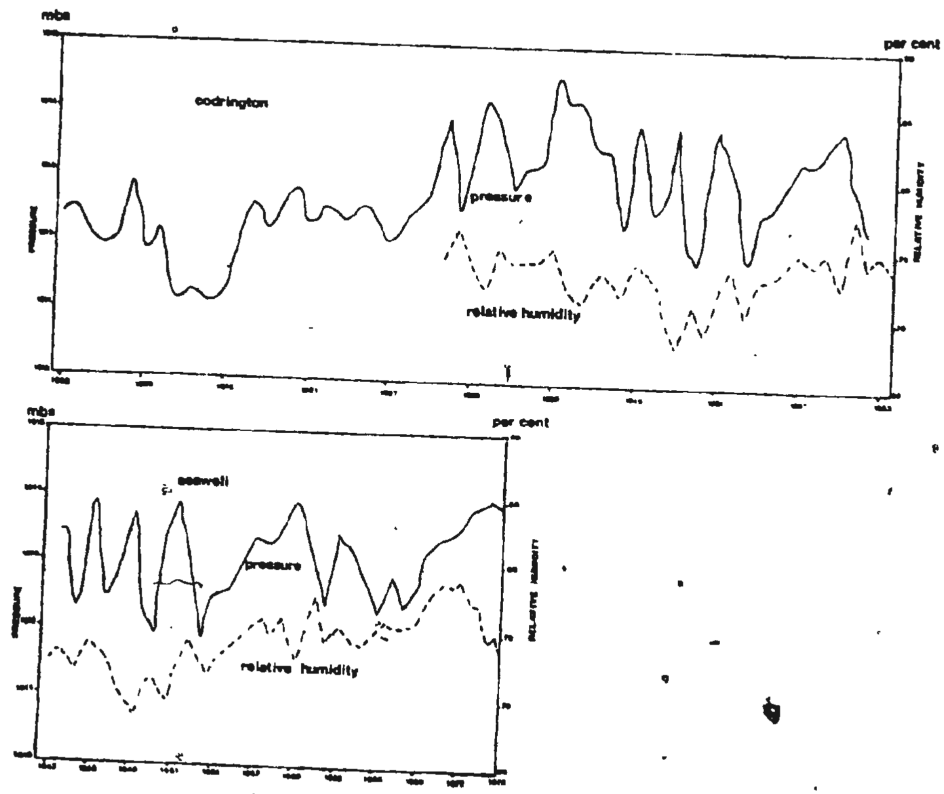
[9]Codrington data cover the years 1931-64, whereas Seawell data span the 34 year period 1942-75.

FIG. 3

MEAN ANNUAL ATMOSPHERIC PRESSURE AND RELATIVE HUMIDITY FLUCTUATIONS AT CODRINGTON AND SEAWELL



H. Rainfall

Rainfall is the only climatic variable which reveals any substantial spatial variation in amount over Barbados (see figure 4). The mean annual rainfall total for the island as a whole is approximately 1397-1524 mm. However, this value can hardly give an accurate assessment of temporal variations in rainfall over the island; for in some years the mean annual rainfall total is significantly higher while in others the value is appreciably lower.

Data from seven carefully selected stations[10] will serve to substantiate this (see fig. 5). For instance, over the period which the data cover the mean annual total rainfall varied from as low as 1136.7 mm. at Central Station, Bridgetown, to as high as 2153.9 mm. at Lion Castle, St. Thomas. Table 1 below gives the mean annual rainfall totals from the seven stations for their respective period of record. But a more meaningful index of temporal variability is the coefficient of variation; this index was calculated for each of the selected stations and ranged from 20.9% to 74%. Barbados rainfall is such a highly variable parameter temporally that a look at Table 2 reveals that in every case, the coefficient of variation exceeds 20%.

It has been found that areas which record the highest rainfall totals also have the lowest coefficient of variation. This again is borne out to a large extent by the data from the seven stations selected (see tables 1 and 2). Similarly, the normal dry season months tend to have far higher

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[10] See Chapter 2 for details of criteria used in selecting rainfall stations.

Table 1

Mean Annual Rainfall for Seven Selected Stations

Station	Altitude	Period of Record	Mean
Central	6.5m	1900-68	1136.7mm
District 'C'	30.5m	1900-75	1293.2mm
District 'E'	30.7m	1900-75	1651.5mm
District 'F'	289.6m	1900-75	1391.9mm
Holetown	2.0m	1900-75	1436.8mm
Lion Castle	274.6m	1900-75	2153.9mm
Searles	85.3m	1900-75	1290.5mm

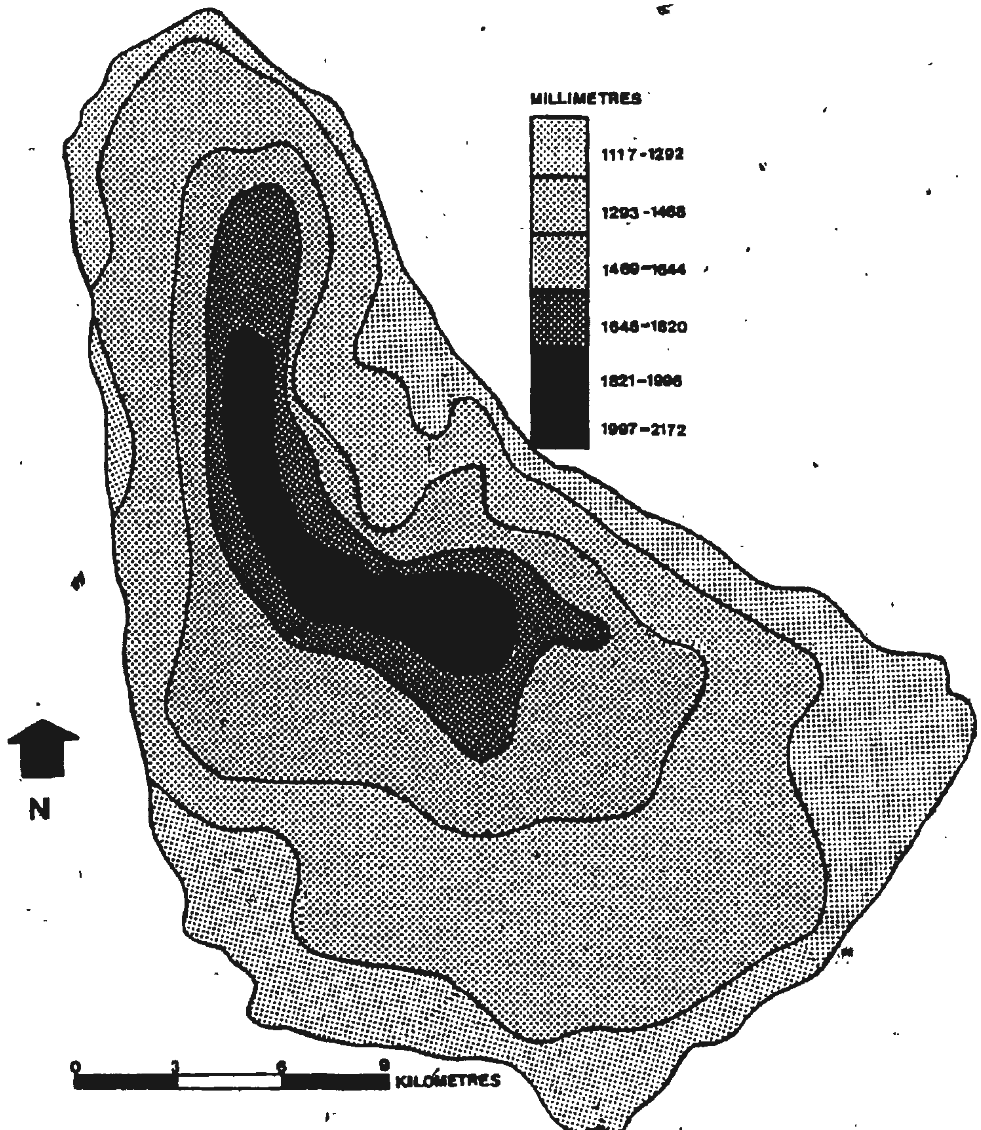
Table 2

Coefficient of Variation of Annual Rainfall for Seven Selected Stations

Station	Location	Coefficient of Variation
Central	13°05'N, 59°36'W	74.0%
District 'C'	13°08'N, 59°29'W	66.5%
District 'E'	13°15'N, 59°37'W	30.4%
District 'F'	13°12'N, 59°33'W	54.7%
Holetown	13°11'N, 59°37'W	49.9%
Lion Castle	13°11'N, 59°35'W	20.9%
Searles	13°05'N, 59°31'W	66.9%

FIG. 4

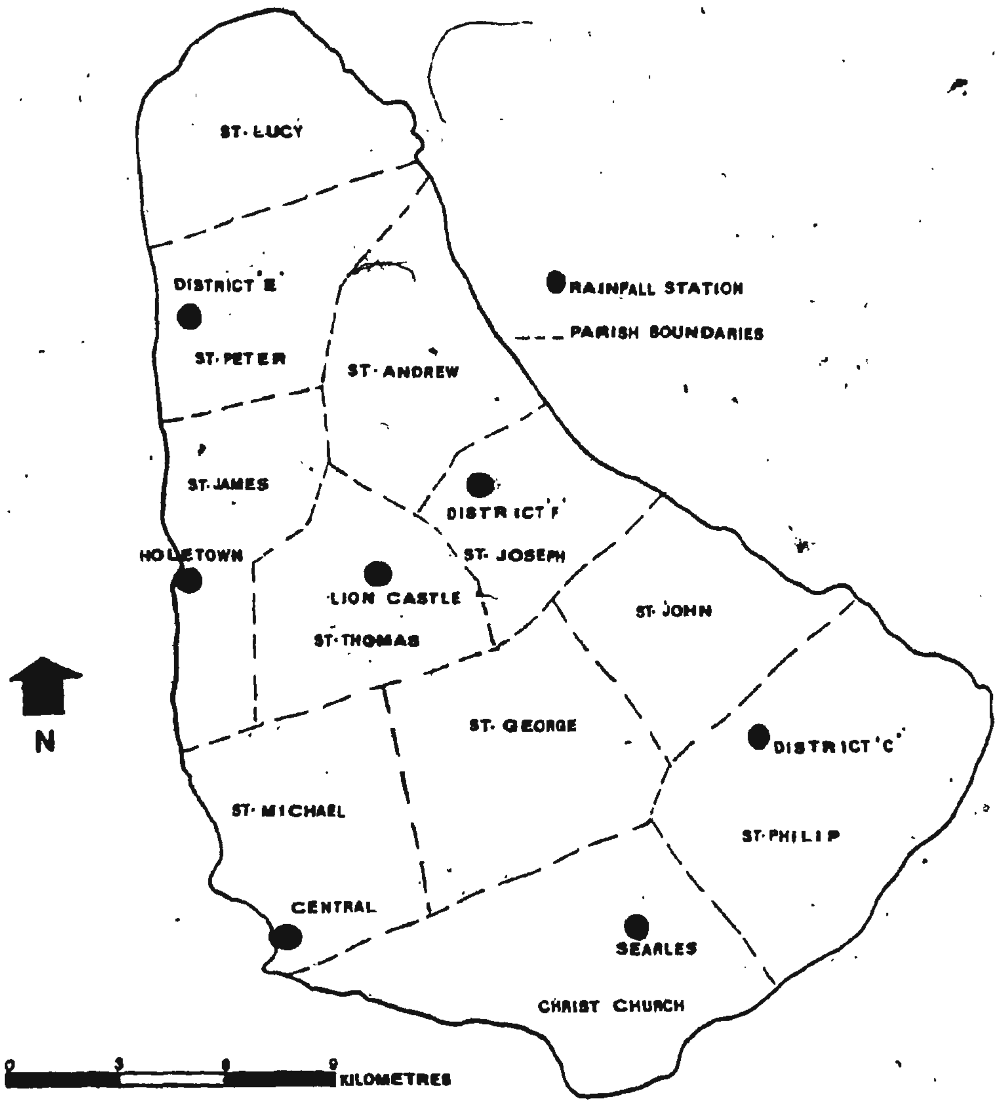
BARBADOS MEAN ANNUAL RAINFALL



(AFTER ROUSE)

FIG. 5

MAP SHOWING LOCATION OF SEVEN SELECTED RAINFALL STATIONS



variability coefficients than those of the wet season. In fact, one recent study has shown that during the dry season the coefficient of variation for most stations on the island exceeds 60%, whereas the index never exceeds 35% during the normal wet season months.[11]

Topography and altitude are also known to exert some influence on the amount and distribution of rainfall over Barbados. In fact, so distinctly marked is this influence that a three-zone rainfall classification, based on altitude, has been proposed for the island. There is a 'low rainfall zone' under 61 metres above-sea-level, which receives between 1117.6- 1447.8 mm., a 'medium zone' above 61 metres but under 244 metres which receives between 1473.2 - 1981.2 mm. and a 'high rainfall zone' above 244 metres which receives a mean annual total exceeding 2006.6 mm.[12] Usually, the greater the elevation of a station, the higher is its mean annual rainfall. Hence, owing to the elevation factor, the central districts of the island generally tend to receive higher rainfall totals than other areas. This spatial disparity in rainfall receipt can be attributed partly to the direct effect of the trade winds blowing from the east and east-north-east in association with altitude.

Altogether, at least 65% of the annual rainfall falls during the normal wet season, leaving only 35% at most for the other part of the year. The extent to which this is demonstrated in the Barbados data is quite remarkable. Taking the wet season as extending from June to November, care-

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11 Lirios, J.F. and Farnum, F.C., A Rainfall Study for Barbados, Part 2. Maps of Isopercental Values and Relative Variability of Rainfall, 1937-70, Caribbean Meteorological Institute, 1972.

12 Rouse, W.R., Moisture Balance of Barbados and its Influence on Sugar Cane Yields - unpublished M.Sc. thesis, McGill University, 1962, p.55.

Table 3

Relative Seasonal Amounts of Rainfall as a Percentage of Annual Total

Station	Dry Season %	Wet Season %
Central	30.6%	69.4%
District 'C'	27.9%	72.1%
District 'E'	31.8%	68.2%
District 'F'	32.0%	68.0%
Holetown	28.5%	71.5%
Lion Castle	29.3%	70.7%
Searles	29.7%	70.3%

ful analysis of the rainfall data for all selected stations shows that mean wet season rainfall ranged from approximately 68-72% expressed as a percentage of the mean annual rainfall total. Table 3 above gives the relative seasonal amounts of rainfall for the seven stations calculated as a percentage of the annual total.

The climate of Barbados then may be described as equable with slight variation. With the exception of rainfall, there is hardly any substantial annual variation demonstrated in the various climatic parameters. Topography and altitude almost totally determine any climatic variation between different locations on the island; these controls are especially determinant in the case of rainfall and cloud cover.

Yet climate, no matter how equable it may seem, is never invariant. Climates at all latitudes have shown fluctuations from time to time, though the rate and direction of change have varied spatially over different time periods. The climate of Barbados is no exception in this respect. For it is against this background that the variations, rhythms, periodicities, if any, and trends in the island's climatic data will be analysed in the chapters which follow.

Chapter 2

Data and Methodology

The present study focuses on three main aims: (i) to identify long-term fluctuations and trends in selected climatic parameters for Barbados since 1900; (ii) to establish the degree and rate of change in frequency of selected synoptic scale weather systems, namely (a) tropical depressions and storms (b) hurricanes (c) local convectional (thunder) storms; (iii) to compare and relate these fluctuations to (a) postulated hemispheric changes and (b) to other low-latitude climatic fluctuations and circulation changes which have recently been observed. Therefore, it is primarily with these objectives in mind that the methodology outlined below was chosen.

A. Data Collection

There are two stations on the island from which data on temperature, pressure, wind, sunshine, relative humidity and cloud amount were available.[13] These are Codrington Climatological Station[14] and Seawell, the island's national weather office. Wind, temperature and barometric pressure data were available for Codrington Station from 1903-1960, humidity from 1931-1964, cloud amount from 1931-1958 and sunshine hours from 1937-1960. Data from Seawell for all the above parameters do not extend as far back in time as those for Codrington and only cover the period 1942-1975.

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[13] All data collected as monthly and annual means.

[14] Codrington Station ceased operation at the end of December 1969. It should further be noted that there is no evidence of inhomogeneity in any of the above weather parameters at the two stations.

These weather data from both stations were compiled following standard meteorological procedure. For instance, the mean monthly temperature data were calculated as:

$$\frac{\text{Mean Maximum} + \text{Mean Minimum}}{2}$$

and mean sea level pressure, humidity, wind and cloud data were computed as the average of readings taken at successive three-hourly intervals, namely 00, 03, 06, 09, 1200, 1500, 1800 and 2100 hours G.M.T. It has already been shown in chapter 1 that with the exception of rainfall there is no significant spatial variation exhibited by these parameters over the island. When these data for Codrington and Seawell were computed over the same period of years (1942-1960), hardly any difference could be found between individual values for the two stations. As a matter of fact the mean annual values of temperature, pressure, humidity and sunshine tended to be very similar in both instances (see Appendix I). Hence, the weather data for the two stations were averaged and the values derived taken as the island mean.

Since one of the main aims of the research was the identification of long-term trends in weather data, it was decided that only rainfall stations with at least fifty years of rainfall data would be used in the analysis. There are presently some forty-eight primary rainfall stations on the island, but of these only eighteen met the above criterion.

The gauge sites at these eighteen stations were visited and assessed in the context of standards laid down by the World Meteorological Organization in 1971.[15] Eleven of the stations were further eliminated because

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[15]See Guide to Meteorological Instrument and Observing Practices - WMO, No. 8, TP. 3, 1971, Geneva, Switzerland, Chapter 7.

of (i) inadequate siting of gauges (ii) frequent shifts in the location of gauges and (iii) several long periods of missing records in the data sets. The seven remaining stations (all of which were used in the study) along with their respective periods of record, approximate altitude and mean rainfall are listed in Table 1.

All rainfall data were made available from the records kept at the Caribbean Meteorological Institude, St. James, Barbados. Data for all other weather variables, including the monthly total number of rain days for five of the sample stations were obtained from the Meteorological Office at Seawell Airport. Locally, a rain day is defined as any day during which at least 0.25 mm. of rain is recorded.

Data on the frequency of tropical storms, hurricanes and local convectional storms were also collected. These were extracted from the records compiled by C.C. Skeete, 1963[16] and 1973[17] and from files supplied by the Meteorological Office. These data cover the period 1900-1975 except in the case of local convectional storms whose data period ends at 1970.

B. Methodological Procedure

Before any form of statistical analysis was attempted all 'raw' data, including rainfall, were key-punched, stored on magnetic tape and plotted by an IBM/System 370 computer. The programme used for plotting

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[16] Skeete, op. cit., pp. 28-36.

[17] Skeete, C.C., The weather in Barbados 1961-1970. Supplement to an Historical Description of the Weather of the Island of Barbados, West Indies During the Period 1901 to 1960. Barbados Gov't Printing Offfice, 1973, pp. 6-8. The writer has been assured, through personal communication with Mr. C.C. Skeete, that the methods and criteria used for identifying these phenomena remained homogeneous for the entire period.

was designed by California Computer Products Incorporated (CALCOMP) in June 1968 and written in FORTRAN G. level language. It utilizes the CALCOMP off-line pen-plotting system. This was done in order to achieve a graphic portrayal of the nature of the temporal and spatial variations represented in the data sets (see Appendix II).

In view of objective (i) above, the method of plotting moving averages was employed to 'smooth' the original data series. Basically, this technique eliminates the rapid, short period, random oscillations in the data set so that the longer period variations can be readily identified. This technique is widely used in studies of climatic change. It has been employed, for instance, by such workers as Callendar (1954), Lamb and Johnson (1959) and Dzerdzeevskii (1963).

The application of the technique is simple and so too are the computations involved. Given any set of values X_1, $X_2 \ldots X_n$ in a time series, a Z-period moving average is defined by a sequence of arithmetic means thus:

$$\frac{X_1 + X_2 + \ldots X_z}{Z}, \quad \frac{X_2 + X_3 + \ldots X_{z+1}}{Z}, \quad \frac{X_3 + X_4 + \ldots X_{z+2}}{Z} \ldots\ldots$$

$$\frac{X_{n+1-z} + X_{n+2-z} + \ldots\ldots X_n}{Z}$$

Five and ten year moving averages were computed for mean annual values of temperature, pressure, relative humidity, wind, sunshine, cloud amount

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and total annual rain days. Where monthly data were used, as in the case of rainfall for the seven sample stations, five, ten and twenty month periods formed the basis for computation of these averages. These specific moving average periods were chosen in order to suppress the amplitude of the known seasonal and annual variations already discussed in chapter 1. The new, smoothed data sequences were also transferred to tape and plotted.

A statistical test of significance was applied to selected sample means extracted from the moving averages calculated. This test was performed in order to determine whether or not there was any significant difference between the mean rainfall of specific fluctuation periods. The test known as the Student's *t* is an index which provides a measure of the relationship between the difference between the means and the standard error of this difference.[18] It is performed by applying the formula:

$$t = \frac{(\bar{a} - \bar{b})}{\sqrt{\frac{\hat{\sigma}_a^2}{n_a} + \frac{\hat{\sigma}_b^2}{n_b}}}$$

where $\bar{a}$, $\bar{b}$ are the means of samples a and b respectively,

$\hat{\sigma}_a^2$, $\hat{\sigma}_b^2$ represent the variance of the two samples,

and n_a, n_b represent the size of the samples a and b, respectively. The level of significance of the index for *t* so derived is determined by applying tables of the Student's *t* distribution, with n-2 degrees of

[18] Gregory, S., Statistical Methods and the Geographer, Longman, 3rd ed., 1973, p. 141.

freedom (see chapter 4).

The method of integral-difference curves was employed in the analysis of the mean annual rainfall data. This involves the calculation of residuals between individual values and population means, which are successively cumulated and plotted. This technique is especially useful for analysing long-term trends in variables which tend to fluctuate rapidly through time. Further, although the resulting graphs do not show actual values, they nevertheless give a clear indication of the onset and ending of fluctuations and provide a good measure of the relative rate of change of trend. Integral-difference curves were used by Kraus[19] in a study of secular changes of tropical rainfall and more recently by Battalov[20] who studied long-term fluctuations of precipitation in the U.S.S.R.

The procedure adopted by Battalov was closely followed in the computation of these residuals. Residual values (K) were derived from the expression:

$$K = \left(\frac{Q_i}{Q_{av}} - 1 \right) - a$$

where Q_i is the rainfall for the ith year of record,

Q_{av} is the long-term mean,

and a is a correction factor computed from:

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[19] Kraus, E.B., "Secular Changes of Tropical Rainfall Regimes," Quart. J. Roy. Met. Soc., 81, 1955, pp. 198-210.

[20] Battalov, F.Z., Long-term Fluctuations of Atmospheric Precipitation and Computation of Precipitation Averages, Trans. from Russian by A. Barouch, edited by P. Greenberg - Israel Program for Scientific Trans. Ltd., 1971.

$$a = \sum_{1}^{i}\left(\frac{\frac{Q_i}{Q_{av}} - 1}{n}\right)$$

where n is the number of years in the data set. The correction factor (a) is applied so that the totals of positive and negative deviations from the mean are equalized. Hence, this has the effect of making the curves symmetrical with respect to the mean line.[21]

The relationship over the period 1900-1975 between rainfall and all other weather variables was investigated. Essentially, this was done in an attempt to determine the best combination of weather variables to which the long-term variance in rainfall at different locations in space could be attributed. It was felt that this type of analysis could throw some light on the possible causes of long-term fluctuations on the island. It was employed to help to determine which specific weather variables, over the period of study, appear to be most closely associated with rainfall fluctuations at individual locations. Canonical correlation was, therefore, selected as the most appropriate analytical device. Basically, canonical analysis describes the intercorrelation between two variable sets. In the case of the Barbados data, the first variable set (the criteria variables) comprised monthly rainfall totals for the seven sample stations, while mean monthly temperature, mean sea level pressure, wind speed, sunshine, relative humidity and cloud amount constituted the variables of the second set (the predictor variables).

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[21]Battalov, op. cit., p. 10.

The application of the technique and the associated mathematical model are explained by Cooley and Lohnes.[22] Given any set of *p* predictor variables and *q* criteria variables, the super matrix $\bar{Y}$ of order $(p + q)$ may be subdivided into four submatrices so that:

$$\bar{Y} = \left[\begin{array}{c|c} y_{11} & y_{12} \\ \hline y_{21} & y_{22} \end{array}\right]$$

where y_{11} is the matrix of inter-correlations between the *p* predictor variables,

y_{22} is the matrix of inter-correlations between the *q* criteria variables,

y_{12} is the matrix of inter-correlations between the *p* predictor and *q* criteria variables, and

y_{21} is the transpose of matrix y_{12}

These submatrices are then substituted into the equation.

$$(y_{22}^{-1}\, y_{21}\, y_{11}^{-1}\, y_{12} - \lambda_i\, I)\ \beta_i = 0$$

where λ_i are the latent roots[23]

I is an identity matrix

and β_i is the characteristic vector associated with the latent roots of the criteria variables computed from:

$$y_{22}^{-1}\, y_{21} - \lambda\, I = 0$$

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[22] Cooley, W.W. and Lohnes, P.R., Multivariate Procedures for the Behavioral Sciences, Wiley, New York, 1962.

[23] The latent root indicates the size of the patterns which are common to the two sets of data.

Similarly, the corresponding vector associated with the predictor variables is calculated from:

$$\alpha_i = (y_{11}^{-1} \; y_{12} \; \beta_i)/\sqrt{\lambda_i}$$

The coefficients α_i and β_i are computed in order to achieve the best correlation estimate between the canonical variates. The canonical correlation (R_c) between the ith pair of composites is the square root of the ith latent root or $\sqrt{\lambda_i}$. The first canonical coefficient determined always shows the strongest correlation between the two sets of variables. All other coefficients portray progressively weaker and possibly lesser important relationships.

The canonical correlates were also tested for significance. This was done by defining:

$$\Lambda = \prod_{i=1}^{q} (1 - \lambda_i); \quad q < p$$

The χ^2 distribution with pq degrees of freedom is related to Λ thus:

$$\chi^2 = - [N - 0.5 \; (p + q + 1)] \; \log_e \Lambda$$

The level of significance of the index thereby derived may then be determined by applying χ^2 tables. It may also be used as a means of testing the null hypothesis (H_o) that the p variates are not related to the q variates.

Since long data sequences were used in this instance, altogether incorporating some 13 different variables, excessive mathematical computations were involved. As a result, the data sets were arranged and coded to meet the specifications of a computer package programme designed to perform canonical analysis. In this regard two separate decks of punched cards were used. On the first set all monthly rainfall data for the seven sample stations were key-punched, while the other deck contained corresponding monthly values for temperature, pressure, wind speed, relative humidity, sunshine hours and cloud amount. The programme was prepared by the University of Alberta, Division of Educational Research Service Computer Program Documentation, August, 1969. It is written in FORTRAN H level language.

Chapter 3

Fluctuations and Trends in Climatic Parameters Since 1900

A. Global Temperature Trends

There is substantial evidence to show that there has been marked variation in global climate and certain identifiable trends in various climatic parameters from earliest civilization to the present. Within recent times climatologists have focussed much attention on this subject and have found varying rates and directions of change both spatially and temporally. Consequently, an extensive literature has been build up around the subject. The work of researchers, such as Lamb (1966), Kraus (1955 and 1958), Bryson (1974) and Kalnicky (1974), are merely a few examples.

In most of these studies, however, workers have tended to concentrate on analysing variation and change in only a few climatic variables, usually air temperature, precipitation or atmospheric pressure. This practice has obvious shortcomings; for these are not all the variables which make up the sum total of climate. It is here contended, therefore, that any study which sets out to analyse climatic fluctuations should embrace as wide a spectrum of variables as possible. In this chapter an attempt will be made to identify fluctuations and trends in various weather parameters recorded at Barbados. These variables include air temperature, atmospheric pressure and wind velocity from 1903-1975; relative humidity and cloud amount from 1931-1975; and hours of sunshine duration between the years 1937-75. One notable exclusion from this list is rainfall; since this variable exhibits such great variation both

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in time and space, it will be analysed separately in the next chapter.

It has been postulated that there was a global increase in air temperature from about the late nineteenth century to about 1940 and a cooling trend since then to the present. For instance, Lysgaard[24] has shown that the increase represented a rise of approximately 0.6°C during this period; a finding which was later substantiated by Lamb and Johnson.[25] At the same time, Longley[26] found a trend of rising temperatures for the whole of Canada from 1900 to 1946, after which period the western half of the country experienced a cooling trend. Similarly, Rubinshstein[27] in a detailed analysis of climatic changes in the U.S.S.R. found a warming trend from about 1880 which culminated in the western part of the country around 1930 but in other areas continued up to as late as 1950.

To some extent there seems to have been some duplication of these postulated temperature trends in some low latitude regions as well. As J.M. Mitchell put it,

> "....the tropics have shared in the secular warming of the past century as well as in a tendency for cooling since the 1940's"[28]

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[24] Lysgaard, L., "Recent Climatic Fluctuations" - Folia Geographica Danica, 5, Copenhagen, 1949, pp. 20-34.

[25] Lamb, H.H. and Johnson, A.I., "Climatic Variations and Observed Changes in the General Circulation", Geografiska Annaler, XLI, 1959, pp. 94-133.

[26] Longley, R.W., Proceedings, Toronto Meteorological Conference - Royal Meteorological Society, 1953, pp. 207-211.

[27] Rubinshstein, E.S., On Changes of Climate in the USSR During Recent Decades; in A.I. Voeikov and the Contemporary Problems in Climatology, Canadian Meteorological Branch Trans. no. 3, Hydromet Pub. House, 1959, pp. 123-174.

[28] Mitchell, J.M., On the Worldwide Pattern of Secular Temperature Change; in Changes of Climate, Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1963, p. 162.

One study undertaken in 1963 suggests that there might have been significant changes in temperature at Algiers and the Northern Sahara region during the twentieth century. For example, the study reveals that during the period 1921-1931 there was an increase of approximately 0.9^{0}C - 1^{o}C over the means of the period 1902-1920.[29] Another study conducted by Hofmeyr and Schulze[30] shows that at stations O'Kiep and Cape Town in South Africa there was an annual temperature increase of nearly 0.3^{o}C between 1901 and 1930, after which the trend continued but at a much reduced rate. These trends have also been identified in areas in and around the Tropical Atlantic. It was noticed that there was an overall rise in air temperature from 1880-1899 to 1940-1949, despite minor fluctuations which did not, in any way, conceal the trend. But more revealing than the trend itself was the spatial variation exhibited within this trend. In areas north of the equator there was a cooling tendency in earlier decades, a minimum between 1910 and 1919, and then an increase which apparently levelled off in the decade 1940 to 1949; in the south west the temperature was found to rise steadily from 1900 to 1909, but thereafter fluctuated haphazardly up to 1940. In the south eastern

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[29] Dubief, J., Contribution to the Problem of Climatic Changes During the Period Covered by the Meteorological Observations Made in Northern Africa; in Changes of Climate. Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1963, pp. 75-79.

[30] Hofmeyr, W.L. and Schulze, B.R., Temperature and Rainfall Trends in South Africa During the Period of Meteorological Records; in Changes of Climate. Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1963, pp. 81-85.

portion of the region, however, there was simply a steady temperature increase from the 1880's to around 1939.[31]

B. Temperature

In order to assess the rate and general direction of fluctuations and trends in the Barbados temperature data, five and ten year moving averages were plotted for mean annual values from 1903 to 1975. It was decided that two sets of moving averages should be plotted for these data as a means of checking whether the initial smoothing process might have been the cause of any apparent but unreal trends. This procedure was suggested by Dzerdzeevskii[32] and has been employed by many workers since then.

It is interesting to note that the two temperature graphs in figure 6 reveal an almost identical pattern. Altogether there were about seven distinct periods of fluctuation thus:

(i) a small but steady increase of approximately 0.3°C between 1903 and 1920;

(ii) an intensification of this upward trend during the decade 1921-1929;

(iii) a decrease between 1929 and 1937 causing temperatures to be similar to what they were during the first two decades after 1900;

(iv) maximum warming between 1937 and 1949 at a rate greater than at any other period;

(v) in the years 1950 to 1959 there was a small but definite decrease;

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[31] Brown, P.R., Climatic Fluctuation Over the Ocean and in the Tropical Atlantic; in Changes of Climate. Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1963, pp. 109-123.

[32] Dzerdzeevskii, B.L., Fluctuations of General Circulation of the Atmosphere and Climate in the Twentieth Century; in Changes of Climate. Proceedings of the Rome Symposium, Organized by UNESCO and the World Meteorological Organization, 1963, pp. 285-293.

FIG. 6

BARBADOS MEAN ANNUAL TEMPERATURE

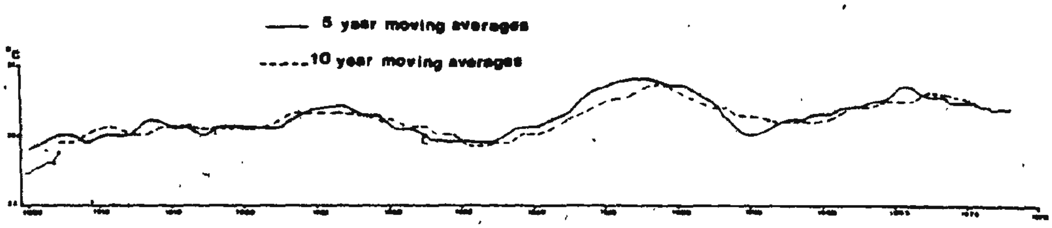


FIG. 7

BARBADOS MEAN AUGUST TEMPERATURE

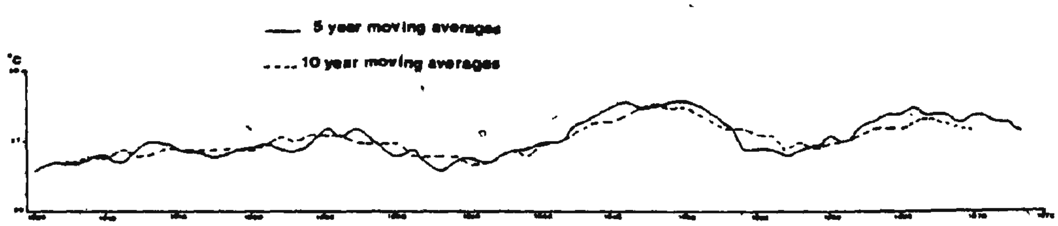
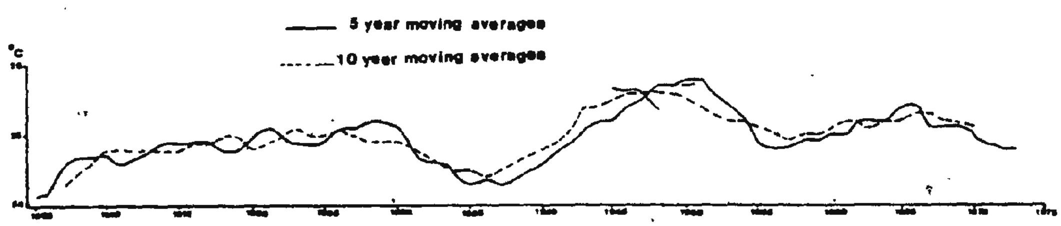


FIG. 8

BARBADOS MEAN FEBRUARY TEMPERATURE



(vi) temperatures rose again from the late 1950's to the late 1960's, but never reached as high as the 1945-50 maximum;

(vii) from the late 1960's to 1975, a slight temperature decrease became evident.

It should be noted that the general trends observed in the Barbados temperature data seem to conform fairly well with patterns detected by other workers in high-latitude regions as well as in other low-latitude areas. It appears, too, that the onset and ending of these trends in the low-latitudes have tended to lag somewhat behind higher latitude areas. In the tropics, the major period of warming (i.e. the 1940's) appears to have started about twenty to forty years later than in the mid-latitudes, whereas it continued for about ten to fifteen years after the so-called *cooling* trend set in in those latitudes. In the case of Barbados, the major warming period started sometime in the late 1930's or early 1940's when temperatures remained almost consistently above the long-term mean of 26.3°C.

Again, there is fairly close correspondence between the rate of increase in temperature in Barbados and the rates calculated for Trinidad and Jamaica. Lamb and Johnson[33] plotted ten and forty year moving averages for Trinidad January and July temperature data for the period 1880-1960. They found a gradual temperature increase of nearly 0:6°C up to the late 1930's or early 1940's after which an apparent gradual decline set in. It might also be mentioned that data for certain mid-latitude

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[33] Lamb and Johnson, op. cit., pp. 120-122.

regions, including north west England and Toronto, were also plotted for comparison; these data closely resembled the pattern exhibited in the Trinidad data series. Recently, an introductory study was carried out on the climate of Jamaica by the Climatology Branch of the Jamaican Meteorological Service. It was discovered that between 1910 and the early 1940's there was a net warming of approximately 0.7 or 0.8°C after which there was a slight decrease up to 1970.[34]

The general patterns as revealed in the Barbados temperature data are also in close phase with those found by Callendar[35] in his study of global temperature fluctuations and trends. He found that between 1880 and 1940, temperatures in tropical regions increased by roughly 0.4°C; but within this zone, the rate of increase varied from as much as 0.7°C in parts of the Caribbbean and India to as low as 0.3°C in Africa and parts of the western Pacific region. But like most other studies of global temperature fluctuations, Callendar also discovered that temperatures rose much higher in extra tropical regions (from the Arctic to 45°N latitude) than in the tropics: in fact, the difference in some cases was as much as 0.8°C or more.

As a further test of the reliability of these temperature fluctuations, five and ten year moving averages were computed for August and February, the warmest and coolest months, respectively. Again, there is striking similarity in these patterns as one might expect; in fact, a

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[34] The Climate of Jamaica, op. cit., p. 31.

[35] Callendar, G.S., "Temperature Fluctuations and Trends over the Earth", Quart. J. Royal Meteorological Society, 87, 1961, pp. 1-12.

comparison of figures 6, 7 and 8 would show a general homogeneity of fluctuations and trends in the three separate data sequences. Not only are the major periods of rise and fall in temperature in correspondence with each other but the approximate dates of commencement and ending of these fluctuations also coincide.

However, there have been slight but important differences in the rates of warming and cooling between the warmest and coolest months. Generally, August temperatures have warmed up and cooled at much the same rate as the mean annual temperature. In absolute terms between 1903 and 1949, August temperatures showed a net increase of approximately 1°C but have showed a net decrease of 0.3°C since then. On the other hand, February temperatures showed a net increase of 1.5°C between 1903 and 1949-50, whereas they have showed a net decrease of almost 0.5°C since then. In other words, even though the general directions and periods of fluctuation have coincided, the month of February has apparently experienced a more rapid rate of warming and subsequent *cooling* than the warmest month, August.

It should be made clear that the so-called global *cooling* trend since the 1940's still constitutes a topic for debate in the climatological literature. In some areas, temperatures appear to be still rising whereas in places such as Australia, the south Atlantic ocean area and the Black Sea-Caspian region, temperatures seem to have remained stable.[36] For it might, in fact, be premature to speak authoritatively of a global

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[36]Callendar, op. cit., p. 1.

cooling trend. As Davitaya warns,[37] it is not yet certain whether this *cooling* since the 1940's

> "...signifies the beginning of a prolonged temperature fall or merely represents a fluctuation on the backdrop of the warming trend which is still continuing."

C. Sunshine

Owing to a lack of data it is almost impossible to establish any trends or fluctuations on the number of sunshine hours on the island of Barbados prior to 1937. However, during the relatively short 39-year period 1937-1975, a few notable fluctuations in this parameter have been observed. Between 1937 and 1948, there was a mean increase of roughly 0.17 hours of sunshine duration; a slight decrease from the late 1940's to the mid 1950's, exceeding that of the 1939-48 period; a major increase from 1956 to 1960; and a net decrease of about 0.3 hours from the early 1960's to 1975. Five and ten year moving averages plotted in figure 9 illustrate these fluctuations in sunshine duration much more clearly.

It appears that the temporal fluctuations in mean annual sunshine hours 1937-1975 have been in general phase with mean annual temperature fluctuations over the same period. It has already been established in chapter 1 that there is some positive correlation between the number of sunshine hours and air temperature. A careful comparison of the graphs in figuers 7 and 9 would serve to illustrate this general relationship. Perhaps it might be quite possible to make certain assumptions and inferences about fluctuations of sunshine duration based on this apparent

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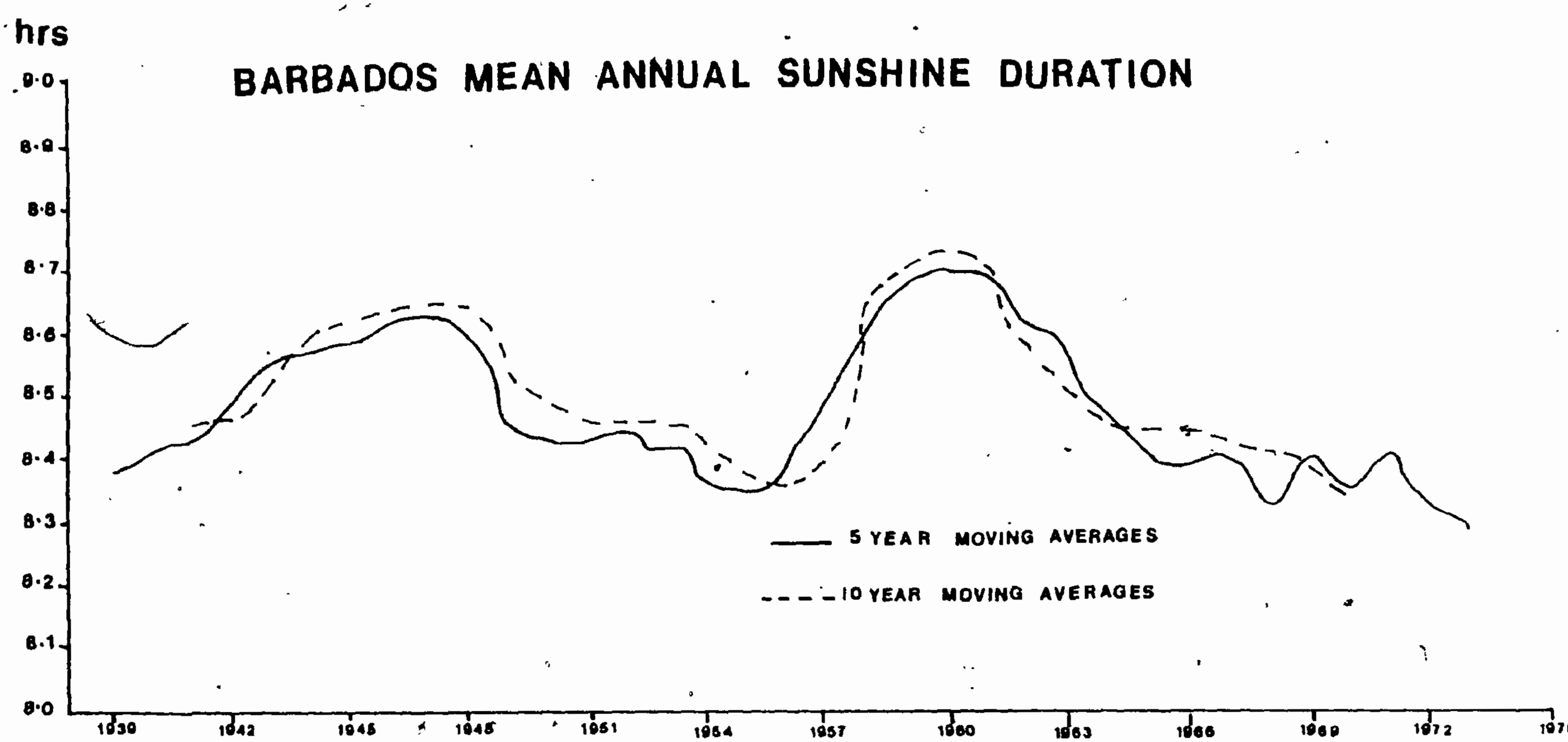
[37] Davitaya, F.F., "Atmospheric Dust Content as a Factor Affecting Glaciation and Climatic Change", Annals Assoc. of American Geographers, 59, 1969, p. 552.

FIG. 9



DATA SOURCE: METEOROLOGICAL OFFICE, SEAWELL

relationship with air temperature. Assuming this general relationship between the two parameters and also that the direction of fluctuations through time have all been the same for both variables, it might be inferred, tentatively at least, that there was slightly less sunshine, per year, prior to the 1940's than after that period. In fact, based on these assumptions it might generally be assumed that the rhythms and trends observed in the temperature data might be applicable in the case of sunshine hours. One should be fully aware, however, of the dangers of these assumptions; the fact that there seems to have been general correspondence between fluctuations in temperature and sunshine hours since 1937 does not necessarily mean that these variables fluctuated in phase prior to then. It should be emphasized that this is not an attempt to reconstruct past data but rather a means of trying to assess how the sunshine parameter might have varied in the recend past.

Some correlation also appears to exist between sunspot relative numbers and sunshine and temperature fluctuations observed in Barbados. According to Waldmeier[38] and Lawrence,[39] the period 1880 to about 1927 was one of small sunspot amplitude, when maxima were generally less than 1500. However, between 1931 and 1960 mean sunspot relative numbers increased significantly above 1500. When Barbados temperature and sunshine data are plotted against sunspot data after Waldmeier, there is an approximate correspondence between the period of low sunspot amplitude and

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[38] Waldmeier, M., The Sunspot Activity in the Years 1610-1960. Zurich Schulthess and Co. A.G., 1961, p. 110.

[39] Lawrence, E.N., "Terrestiral Climate and the Solar Cycle", Weather XX, no. 11, 1965, pp. 334-343.

relatively low temperatures, and high sunspot amplitude and increasing air temperatures and sunshine hours (see figure 10). Similar relationships between temperature and sunspots have been suggested by Lawrence[40] for data from Edinburgh, Wakefield and Greenwich in the British Isles. Similarly, A.J. Troup[41] using temperature data from a few selected stations, postulates that the apparent relationship between increasing sunspot numbers and rising temperatures is applicable to nearly the whole of the tropics.

Although no cause and effect relationship is necessarily implied here, it is being suggested that changes in temperature, sunshine duration and probably radiation might be linked with the sunspot cycle and changes in solar output. In turn these variations could conceivably be associated with changes in the general circulation of the atmosphere which, it is suggested, might well explain most of the major global climatic fluctuations. This theory has already been postulated by many climatologists, notably Lamb and Johnson[42] and Kalnicky,[43] even though they have not been able to establish the exact nature of such relationships.

D. Cloud Cover

There have been a few notable changes in mean cloud cover over

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[40] Ibid., p. 339.

[41] Troup. A.J., "A Secular Change in the Relation Between the Sunspot Cycle and Temperature in the Tropics", Geofisica Pura e Applic., 51, 1962, p. 184

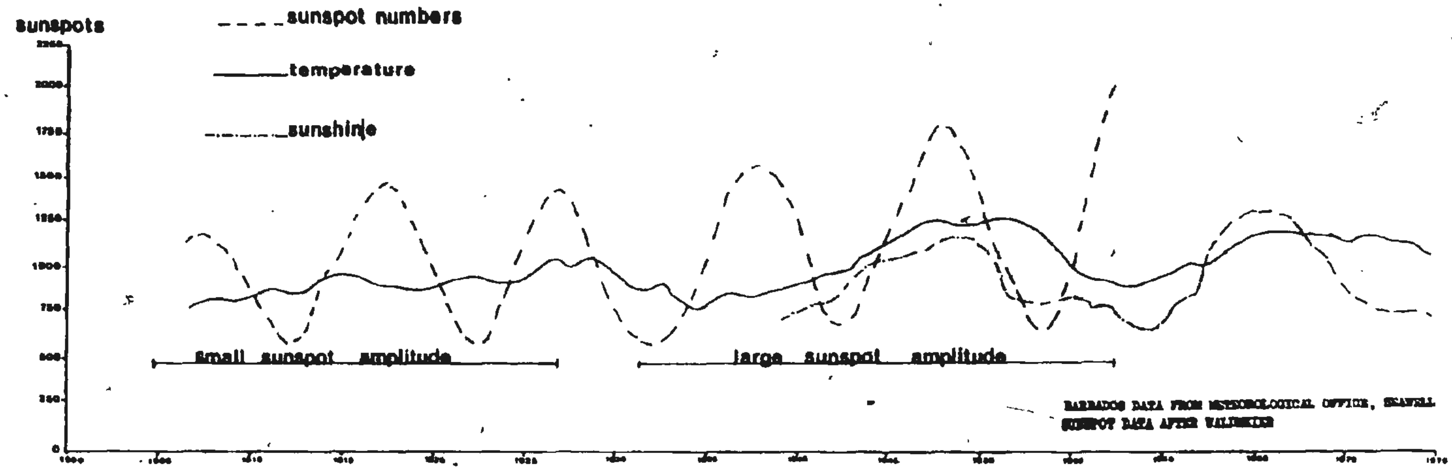
[42] Lamb and Johnson, op. cit., pp. 94-133.

[43] Kalnicky, R.A., "Climatic Change Since 1950", Annals Assoc. of American Geographers, 64, 1974, pp. 100-112.

FIG. 10

RELATIONSHIP BETWEEN SUNSPOT AMPLITUDE AND BARBADOS TEMPERATURE AND SUNSHINE VARIATIONS

5 year moving averages



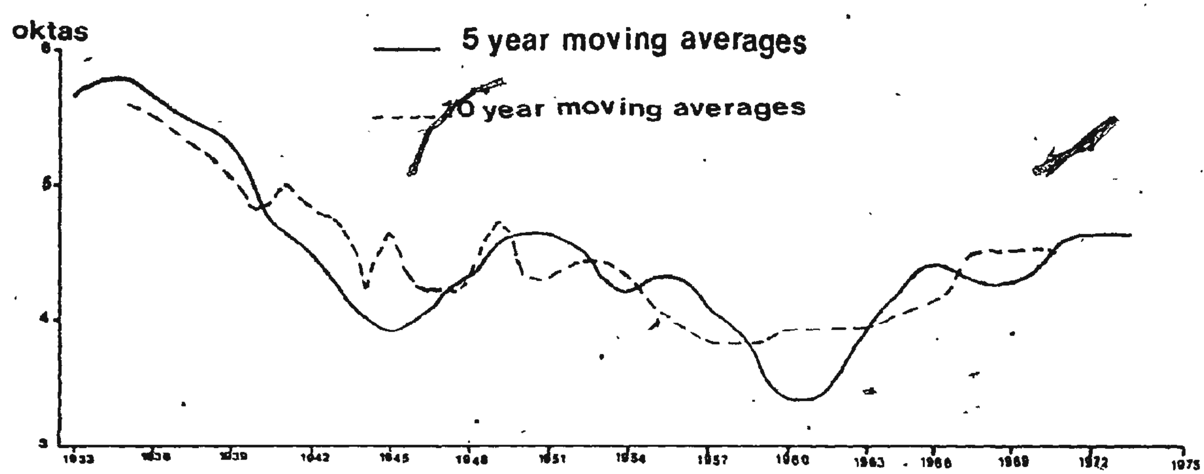
Barbados during the years 1931 to 1975. Broadly, three main periods of fluctuation can be observed (see figure 11). There was a steady mean annual decrease form 1931-1945; an intensification of this trend with minor fluctuations, from 1945 to the late 1950's or early 1960's; and a relatively steady increase since then. Generally therefore, there was a downward trend in mean annual cloud amount for the first three decades after 1931, with a maximum rate of decrease of about 0.07 oktas per annum in the period 1945-1960. Thereafter, there has been a tendency towards increasing could amount at a mean annual rate of approximately 0.05 oktas. It is still too early, however, to state explicitly whether this latter upward tendency is, in fact, the commencement of a prolonged trend or simply a major fluctuation temporarily interrupting the downward trend.

One noteworthy observation is an evident inverse relationship between temperature fluctuations and variations in cloud amount. For whereas the temperature data reveal an upward trend into the late 1940's or early 1950's, mean cloud amount has trended in a generally opposite direction. Likewise, the recent tendency towards decreasing temperatures seems to be counterbalanced by a tendency towards increasing cloud amount. If reference were again made to figures 6 and 11 this inverse relationship would become more apparent.

The apparent negative correlation between temperature and cloud, though striking, is not altogether an unexpected one. A basic understanding of the seasonal variations exhibited in the parameters not only suggests but also partly explains such a relationship. As demonstrated in

FIG. 11

BARBADOS MEAN ANNUAL CLOUD COVER



DATA SOURCE: METEOROLOGICAL OFFICE, SEAWELL

chapter 1, mean daily cloud amount tends to be higher during the cooler, wet season than in the warmer, dry season; hence, it should normally be expected that any increase (decrease) in mean annual temperature would be associated with a decrease (increase) in mean annual cloud amount.

E. Pressure and Wind

It was suggested in chapter 1 that there is some similarity between the annual regime of atmospheric pressure and wind speeds in Barbados. It was felt that since the two regimes are virtually similar, any fluctuations in one over a period of years ought to be associated with similar variations in the other. In order to test the reality of this assumption, mean annual data for both parameters, 1903-1975, were smoothed by five and ten year moving averages and plotted for comparison.

The comparison between figures 12 and 13 is not quite as good as might have been expected. For the fluctuations in atmospheric pressure and wind velocity only appear to be in direct phase during the post-1940 period. Prior to then, most of the fluctuations seem to have been slightly out of phase. In the case of atmospheric pressure, there was a marked net increase from 1903 to 1940 of about 2 millibars. In contrast, wind velocity during the same period showed a slight net decrease of nearly 0.5 ms^{-1} with shorter period fluctuations. However, after 1940 there was a gradual decrease in air pressure into the 1960's, which averaged about 0.7 millibars less than the 1930-1940 mean. In the case of wind velocity, there was a slight intensification of the previous downward trend which also lasted well into the 1960's. From the 1960's to 1975

FIG. 12

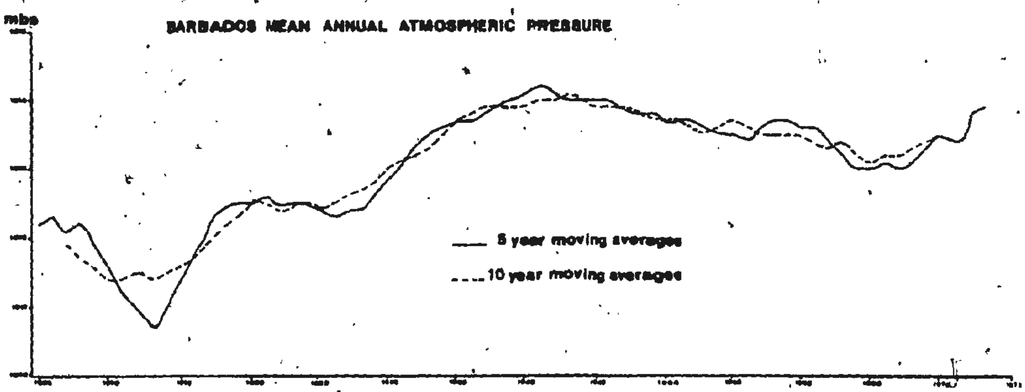
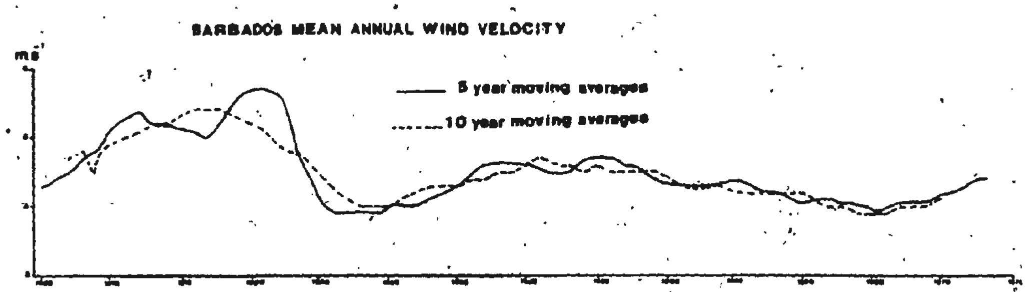

mbs
BARBADOS MEAN ANNUAL ATMOSPHERIC PRESSURE
5 year moving averages
10 year moving averages

FIG. 13


BARBADOS MEAN ANNUAL WIND VELOCITY
ms⁻¹
5 year moving averages
10 year moving averages

both mean atmospheric pressure and mean wind velocity have shown somewhat of an upward tendency, the respective rates of increase being approximately 0.05 millibars and 0.03 ms^{-1} per annum, respectively.

Lamb and Johnson[44] found a definite tendency for the frequency and intensity of the North-east Trades to increase whenever the North Atlantic Westerly circulation increased. They correlated indices of the Westerly circulation (40–50°N, 40°W) and the Trades (30-10°N, 60°W) for January over a 79-year period and found the correlation coefficient $r = 0.53$, significant at the 0.1% level. This tendency seems to be borne out in large measure when Barbados wind data and Lamb's Westerly circulation indices 1900-1969 are compared. Figure 14 suggests that there was strengthening of both circulatory systems between 1900 and 1929 but a gradual weakening over the next four decades. The fact that these two systems show a tendency to fluctuate in phase with each other seems more than an occurrence of chance. For although it is difficult to define it as present, there appears to be an important physical relationship between the circulation of the Easterly and Westerly belts.

Like temperature, most of the variations observed in the Barbados pressure data are not incompatible with the major trends in these indices postulated by other researchers for the Northern Hemisphere. For instance, Lysgaard[45] found that during the years 1910–1940, mean summer and winter values of atmospheric pressure showed an upward trend over the southern North Atlantic. An examination of the Barbados pressure data for the

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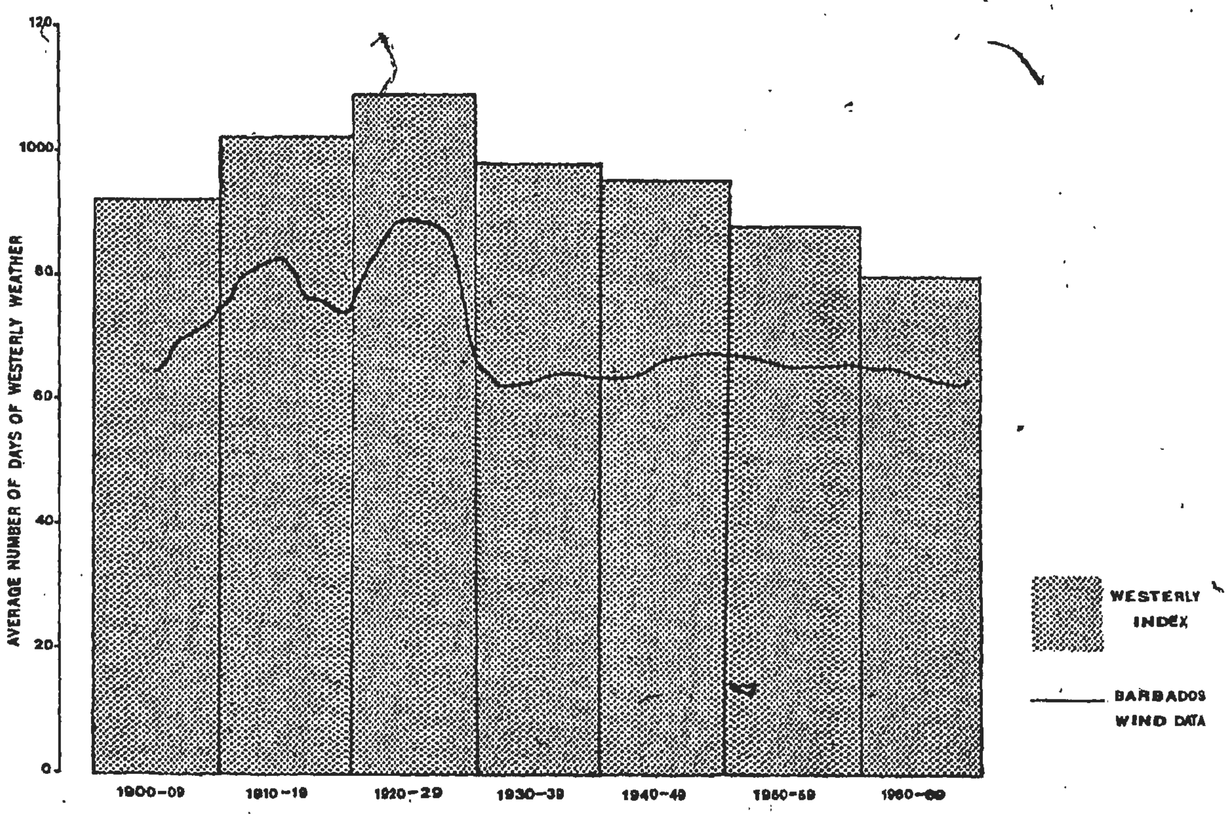
44Lamb and Johnson, op. cit., p. 115.

45Lysgaard, op. cit., p. 25.

FIG. 14

RELATIONSHIP BETWEEN THE INTENSITY OF LAMB'S WESTERLY INDEX AND BARBADOS MEAN ANNUAL WIND VELOCITY



WESTERLY DATA AFTER LAMB et. al.
BARBADOS DATA FROM METEOROLOGICAL OFFICE, SEAWELL

same period reveals a close similarity of trend. In a more recent study Lloyd[46] found a steady upward trend in pressure from 1880 to the 1940's at Santiago, Chile, after which period a gradual decline set in. These trends again show good correspondence with variations observed at Barbados.

F. Relative Humidity.

There are no humidity data available for the island prior to 1931, hence, any assessment of the nature of variations in this parameter before this date must be largely speculative. From the limited data available only two major periods of fluctuation are discernible. In the first place there was a decrease in mean annual relative humidity between 1931 and 1948; the net decrease during this period was apporximately 3 or 4 per cent. In contrast however, there was a steady upward trend after that period, the net increase being roughly 6 per cent.

Since humidity is known to show good correlation with air temperature, it should normally be expected that there might be some clear association between fluctuations in the two parameters over a given time period. However, there is little evidence of such an association when the mean annual temperature graph is compared with the humidity curves in fig. 15. But it should not be assumed that variations exhibited by the two parameters are unrelated; for it is acknowledged that there is a strong physical relationship between these parameters. Not unexpectedly however, when the humidity graphs are compared with the curves showing air pressure, the fluctuations tend to be generally in opposite directions. It may be recalled

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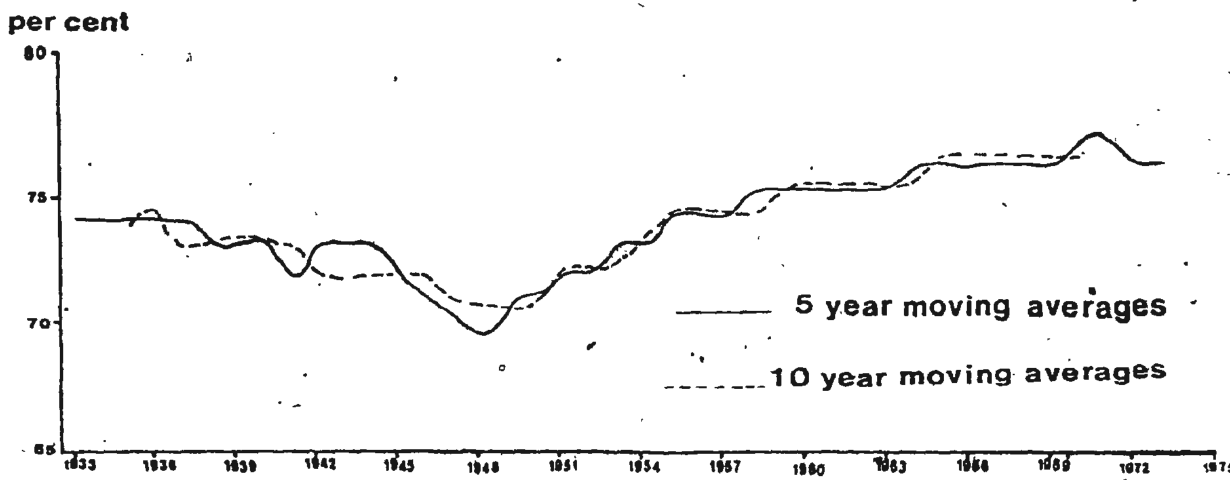
[46]Lloyd, J.W., "Climatic Variations in North-Central Chile from 1866 to 1971", Journal of Hydrology, 19, 1973, pp. 60-62.

FIG. 15

BARBADOS MEAN ANNUAL RELATIVE HUMIDITY



DATA SOURCE: METEOROLOGICAL OFFICE BRAWELL from chapter 1 that in terms of the annual variation the months of higher relative humidity are generally positively correlated with the months of lower mean atmospheric pressure.

G. Some Postulated Theories of Recent Climatic Change

Several hypotheses have been advanced to account for known global climatic fluctuations which have recently been observed. It has to be admitted, however, that most of these theories are still speculative since quite a lot still remains to be known about the dynamics of atmospheric motion. Although various links and associations have been suggested among such indices as changes in solar output, increase in atmospheric carbon dioxide and changes in terrestrial climatic indices, no single theory yet advanced seems capable of explaining observed fluctuations.

For instance, authors including Godson[47] and Sawyer[48] have suggested that recent climatic fluctuations might be due to variations in solar radiation which in turn could obviously effect changes in atmospheric motion. However, there is, so far, not enough evidence to prove any significant variation in the sun's radiative energy. Although sunspot relative numbers have tended to increase since the 1800's up to the mid 1900's and have correlated quite well with the earlier warming trend, no significant changes have been detected in the intensity of solar radiation. Hence, for the time being at least, this theory can only be accpeted with the utmost caution, if at all.

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[47] Godson, W.L., The Influence of the Variability of Solar and Terrestrial Radiation on Climatic Conditions; in Changes of Climate. Proceedings of the Rome Symposium Organized by UNESCO and the World Meteorological Organization, 1963, pp. 323-331.

[48] Sawyer, J.S., Notes on Possible Physical Causes of Long-term Weather Anomalies. Technical note no. 66, WMO no. 162 TP 79, Geneva, 1965, pp. 227-248.

Wexler[49] postulated that the global trend of rising temperatures was due mainly to a reduced number of large volcanic eruptions capable of injecting large amounts of dust into the atmosphere. He contended that any decrease in volcanic dust could increase the transparency of the atmosphere for solar energy. However, it has since been indicated by Callendar that only the short term fluctuations in temperature can thus be accounted for, not the long-term trends. He argues:

> "For example, the high altitude dust from Krakatoa 1883 and Pelee 1902, could have caused the sharp (temperature) falls ... about those dates and the absence of concurrent fluctuations since 1920 might be attributed to a lack of explosive eruptions of sufficient size to affect the whole earth."

But he continues:

> "...the problem is very complex and it would be difficult to explain the big oscillations about 1912-20 on the basis of the Katmai eruption in 1921 or the fact that the many eruptions since 1920 do not appear to have had a significant effect on the zonal fluctuations. Evidently, there are other factors at work besides volcanic dust."[50]

Similarly, the same author points out that if the rise in temperature was caused by increased atmospheric transparency or increased solar energy, *sunny* sub-tropical areas should record a greater rate of increase than areas of the *cloudy* North Atlantic. Yet, the data show the reverse to be true; and in some cases, no rising temperature trend has yet been observed in parts of the sub-tropics.

It was contended by Plass[51] and later argued by Callendar[52]

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[49] Wexler, J., Climatic Change, Harvard University Press, 1953, pp. 75-104.

[50] Callendar, op. cit., p. 9.

[51] Plass, G.N., "The Carbon Dioxide Theory of Climatic Change," Tellus 8, 1956, p. 140.

that the recent temperature trends could be attributed to increased carbon dioxide content of the atmosphere produced by the burning of fossil fuels. They contend that an increase of CO_2 would cause increased back radiation and hence, account for the warming trend since the 1900's. They have also demonstrated that:

(i) there is a large, though as yet unknown, time lag in the transport of excess CO_2 from the point of greatest production (middle northern latitudes) to southern latitudes; hence, a greater rate of warming in more northerly latitudes than southerly;

(ii) there has been a tendency for precipitation to decrease in tropical regions in the first four decades of this century as shown by Kraus.[53] The explanation here is that since the amount of precipitation is a "measure of the latent heat released at the cloud level", any retarding influence on the loss of such heat would slow down convection currents and reduce precipitation - this effect can be accomplished by an increase of CO_2 in the atmosphere.

Nevertheless, plausible though this theory may seem, it must be reexamined in the light of other important data. There is no doubt that fossil fuel combustion and CO_2 emissions have been greater in the post 1940-50 period than in previous decades. This almost phenomenal increase in fossil fuel combustion, atmospheric dust and CO_2 has been well demonstrated and documented by many climatologists including Davitaya[54] and Robinson.[55] In fact, Robinson has shown that the CO_2 content of the

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[53] Kraus, 1955, op. cit., pp. 201-203.

[54] Davitaya, op. cit., pp. 552-559.

[55] Robinson, G.A., Physical Causes and Possibilities of Climatic Change in Kopec, R.J. (ed.) Atmospheric Quality and Climatic Change, University of North Carolina, Dept. of Geog., Studies in Geography No. 9, 1976, pp. 65-75.

atmosphere has increased by roughly 10 per cent in the present century; doubtlessly, the major proportion of this increase has come about in the last few decades associated with an upsurge in industrialisation and urbanisation. Taking this into consideration, therefore, theoretically the warming trend should have intensified, especially in mid-latitude regions where the greatest expansion of industry has taken place. But this has apparently not been the case; for the so-called *cooling* trend which seems to have set in in recent decades hardly supports the hypothesis. Furthermore, this cooling tendency after the 1940's is believed to be occurring more rapidly in high and mid-latitude regions than in the lower latitudes.

It is contended here that climatic fluctuations are not affected by, neither are they the result of, a single factor or process; but rather a combination of interacting factors and processes. Yet, as a single unified theory, the hypothesis involving changes in the general circulation of the atmosphere seems to explain satisfactorily most of the recent climatic variations observed. It has been demonstrated by Lamb and Johnson[56] and more recently by Kalnicky[57] that recent changes of precipitation, atmospheric pressure and temperature have been associated with adjustment in the hemispheric circulation pattern. In fact, Kalnicky has shown that most of the recent global changes of climate have been directly associated with variations in circulation indices; from predominantly zonal between 1900 and 1950 to more meridional since then.

The extent to which indices of the general circulation have changed and the extent to which they are associated with other climatic fluctua-

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[56] Lamb and Johnson, op. cit., pp. 98-130.

[57] Kalnicky, op. cit., p. 100.

tions in Barbados, especially with respect to rainfall, will be analysed in the ensuing chapter.

Chapter 4

Rainfall Fluctuations and Trends

A. Long-term Variations in the Island Rainfall Regime

Rainfall in the small island of Barbados exhibits a marked spatial pattern. It has been shown elsewhere that the pattern of rainfall distribution is very much related to the nature of the atmospheric circulation, topography, altitude and season. A few studies investigating the annual march of precipitation and also the characteristics of the resulting spatial pattern have previously been undertaken. For instance, research by Oyelese (1962), Rouse (1966) and Lirios and Farnum (1972) confirms the extent of the annual and spatial variation in the rainfall statistic. However, no study of the long-term flucuations and trends in the island's precipitation regime has ever been undertaken; hence, in this chapter an attempt will be made to analyse the major periods of fluctuation in this parameter between 1900 and 1975.

Generally, there are three main types of rainfall experienced in Barbados the nature of which, to a large extent, determines the observed spatial pattern. These are what may be referred to as the "regional rains", the "surface-heating type" or "local convectional rains" and the so-called "hurricane rains".[58] The first type is associated primarily with the intensity and persistence of the north-east trade wind circulation and is experienced in all caribbean islands. This is vitally important, especially to the eastern parishes, since very often these areas are not much affected by local convectional rains. Local convectional rains, which will be discussed in greater detail in Chapter 5, tend to be most prevalent between

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[58]Skeete, C.C., Barbados Rainfall, Dept. of Science and Agriculture Bulletin No. 9, pp. 25-49, 1960.

the months of July and November. They are usually the result of a combination of high temperatures and low wind speeds and their effects are most strongly felt in central, western and northern parishes. The hurricane type, as the name implies, is directly associated with the passage of tropical depressions, storms and hurricanes and is generally associated with showers of very great intensity. Thus, the seasonal and annual variation in rainfall amounts from place to place is largely controlled by the vigour and persistence of these three types.

During the last two decades or so various workers have conducted research into the nature and rate of change of climate and atmospheric circulation within the tropics. For the most part, these studies have tended to concentrate on precipitation fluctuations and have generally found a trend towards decreasing rainfall, with major fluctuations since the turn of the century. The work of Kraus (1955 and 1958), Lamb (1966) and Hofmeyr and Schulze (1963) are outstanding examples in this respect. In fact, it has even been predicted by Lamb[59] that droughts will continue to show an increase in freuqnecy and that the present dry phase will probably continue for some time yet in most areas of the tropics.

Generally, there appears to have been seven distinct periods of fluctuation exhibited in the Barbados mean rainfall data.[60] The graphs of five and ten years moving averages plotted in figure 16(a) indicate:

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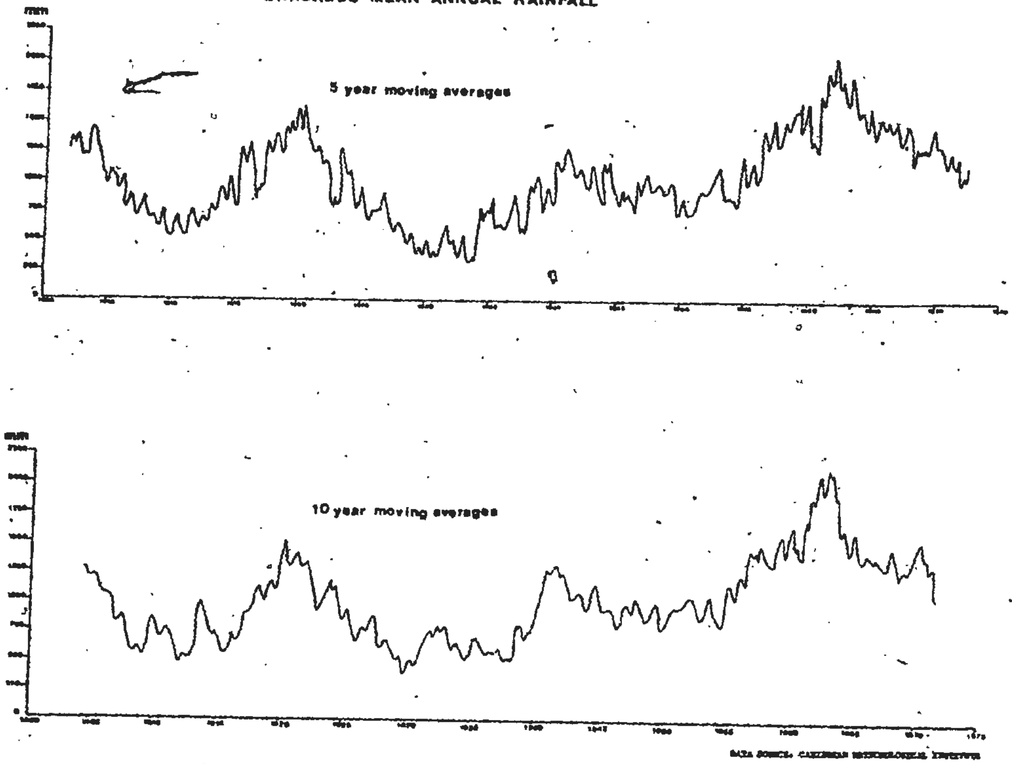
[59] Lamb, H.H. quoted in Drought in Africa, edited by D. Dalby and R.J. Harrison Church. School of Oriental and African Studies, London, 1973, pp. 27-28.

[60] These data represent the averages of returns for all of the island's forty-eight primary rainfall stations.

BARBADOS MEAN ANNUAL RAINFALL



(i) a minor downward trend from 1900 to approximately 1911;

(ii) a major upward fluctuation from 1911 to 1920;

(iii) a rapid, pronounced downward trend from 1920 to 1930;

(iv) a period of increasing rainfall from the early 1930's to about 1940

(v) an increasingly dry phase from the 1940's until about 1949;

(vi) a major upward trend thereafter until the late 1950's or early 1960's

(vii) a steady decrease from the 1960's to the present.

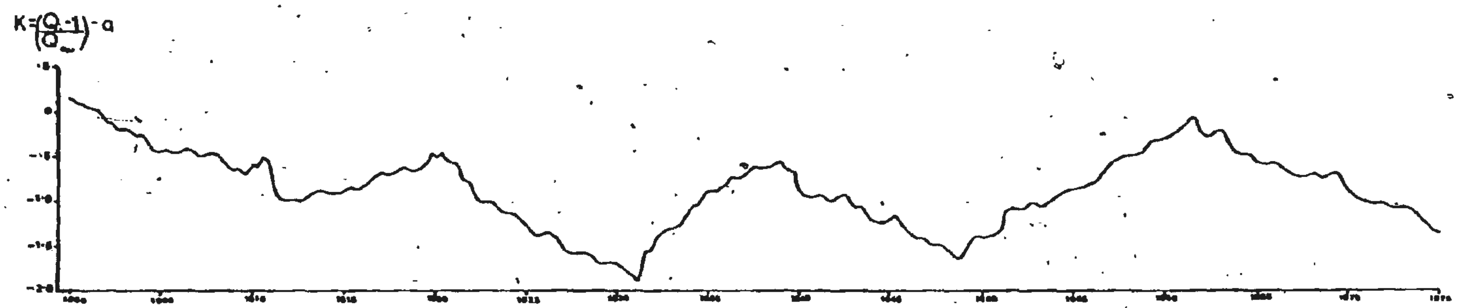
It is remarkable that integral-difference curves plotted for the same data reveal a similar cyclic pattern and, in fact, the commencement and ending of each period of fluctuation roughly coincide (see figure 16(b)). The fact that these curves are broadly similar suggests that the fluctuations identified can be considered as indicative of real changes in the island's rainfall regime; and thereby tends to eliminate the possibility that they might have been artificially produced by the method of smoothing.

A comparison of sample means for selected periods of fluctuation gives some very interesting results which further tend to confirm the existence of these rainfall changes. For instance, between the years 1911 and 1920 the island mean annual rainfall was approximately 7 per cent and 18 per cent higher than the means of 1900-11 and 1921-30[61], respectively. Similarly, during the years 1950-63, the period of highest mean annual rainfall for the entire data set, mean annual rainfall was 21 per cent

[61]This was easily one of the driest periods in the known climatic history of the Caribbean.

FIG. 16(b)

INTEGRAL-DIFFERENCE CURVE FOR ISLAND MEAN ANNUAL RAINFALL



DATA SOURCE: CARIBBEAN METEOROLOGICAL INSTITUTE

and approximately 11 per cent higher than the annual means for the respective periods 1921-30 and 1964-75. The absolute values of mean annual rainfall for each period of fluctuation listed above are given in table 4. Further, it should be stated that for the most part the differences between the sample means for successive periods of fluctuation have been found to be statistically significant from the 2.5% level and up. The only exception is the difference between the means of the fluctuation periods 1931-40 and 1941-49. For although the graphs indicate a difference in the general direction of trend, the sample means were not significantly different and when tested by Student's t (t = 1.3) barely reached the 10% level of significance. Table 5 gives a list of each pair of sample means compared, the index value for t and the level of significance for each index.

It has already been demonstrated in chapter 1 that the slight variation observed in the temperature regime is partly attributable to rainfall receipt. Since it is known that periods of high rainfall usually bring about a reduction in air temperature, it might be expected that years of high rainfall should coincide roughly with periods of reduced temperatures. When the temperature graph in figure 6 was compared with the rainfall curve in figure 16(a), it was found that there was a general tendency for periods of higher rainfall and lower temperatures to coincide approximately. The only exceptions were the years 1911-20 when rainfall showed an upward fluctuation (and so too did temperature) and the period 1964-75 when the fluctuations in both parameters were generally in a downward direction.

Table 4

Periods of Fluctuation and Mean Rainfall for Each Period

Barbados Mean Annual Rainfall

Period of Fluctuation	Mean Rainfall (mm)
1900 - 11	1402.4
1912 - 20	1501.3
1921 - 30	1230.0
1931 - 40	1454.2
1941 - 49	1434.1
1950 - 63	1551.5
1964 - 75	1390.1

Table 5

Significance Levels for Differences Between Sample Means for

Selected Periods - Barbados Mean Annual Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	t	Significance level
1900-11	1912-20	1402.4	1501.3	2.07	.025
1912-20	1921-30	1501.3	1230.0	2.81	.005
1921-30	1931-40	1230.0	1454.2	2.56	.01
1931-40	1941-49	1454.2	1434.1	1.30	.10
1941-49	1950-63	1434.1	1551.5	2.52	.01
1950-63	1964-75	1551.5	1390.1	2.09	.025

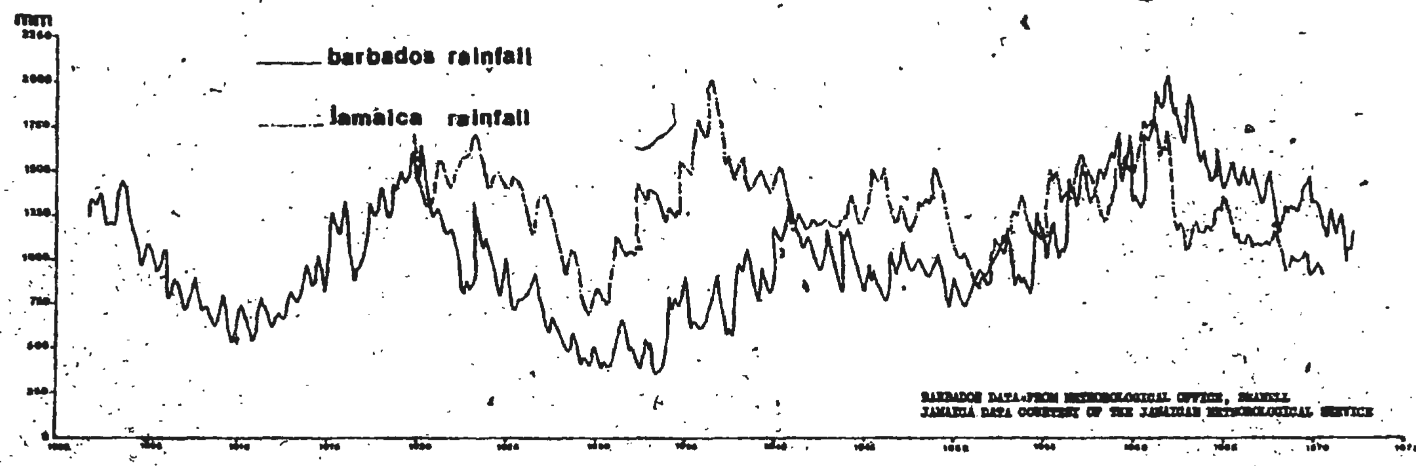
It is interesting to note that the fluctuations exhibited in the Barbados mean rainfall data show rough similarity with the pattern identified in the Jamaica data. Figure 17 gives a graphic portrayal of this comparison. For although the onset and ending of these fluctuations appear to lag behind or precede each other by a few years, the general tendency for each pair of fluctuations to trend in the same direction is clearly evident. Perhaps it may be that this general cyclic pattern is representative of the entire Caribbean region, but this could only be ascertained by further analysis of long period rainfall data from other islands. It would not at all be surprising if this were the case, since the climates of the whole chain of islands are largely controlled by the same mechanisms of atmospheric circulation; namely the north-east trades in association with the Bermuda-Azores high. Hence, there is the likelihood that any long-term variations in the climatic regime at any point might be associated with similar variations at most other locations in the region.

B. Spatial Variation in Long-term Pattern

It has previously been demonstrated that rainfall exhibits a marked spatial pattern across the island. This pattern is characterized not so much by a difference in regime as it is by differences in amount of rainfall recorded at different locations. Hence, more detailed sequences of data, namely monthly total rainfall amounts for the seven selected stations, were examined for variations in the long-term pattern exhibited by the mean island data. It was found that the trends and fluctuations shown in

FIG. 17

5 YEAR MOVING AVERAGES FOR BARBADOS AND JAMAICA MEAN ANNUAL RAINFALL



the rainfall regimes of the seven sample stations were generally in phase not only with each other but also with the rhythms shown in the island data. The recurrence of this pattern, therefore, strongly suggest it to be representative of temporal variations for the island as a whole. However, within this overall pattern there is a noticeable spatial pattern, which is characterized by the *timing* of each period of fluctuation.

Five, ten and twenty month moving averages for stations District 'E' and Holetown show that between 1900 and 1913 there was a gradual decrease in monthly rainfall but an upward fluctuation from then until 1919. From about 1919 to 1930 there was a major decrease in rainfall, whereas for the next nine or ten years there was a noticeable increase. A slight downward fluctuation occurred from the late 1930's until the mid to late 1940's, after which period a major increase in rainfall was recorded until the mid 1960's. A gradual but significant downward trend then set in and continued up to 1975 (see figs. 18(a) and 18(b)). In both cases, the rates of change of fluctuation were approximately similar and the *timing* of the fluctuations has been almost synchronous. At both stations which are located on the island's west coast, mean monthly rainfall was around 5 per cent more in the period 1914-1919 than it was between 1900 and 1913, whereas the 1920-30 mean was 19 per cent less than that for 1914-1919. At the same time there was roughly 22 per cent more rainfall recorded in the years 1947-65 than in the 1920-30 period; and the decrease between 1966 and 1975 represents a monthly average of about 6 per cent less than the average for 1947-65. Again, the differences between sample means for selected periods of fluctuation were found to be generally significantly different

FIG 18(a)

DISTRICT E RAINFALL

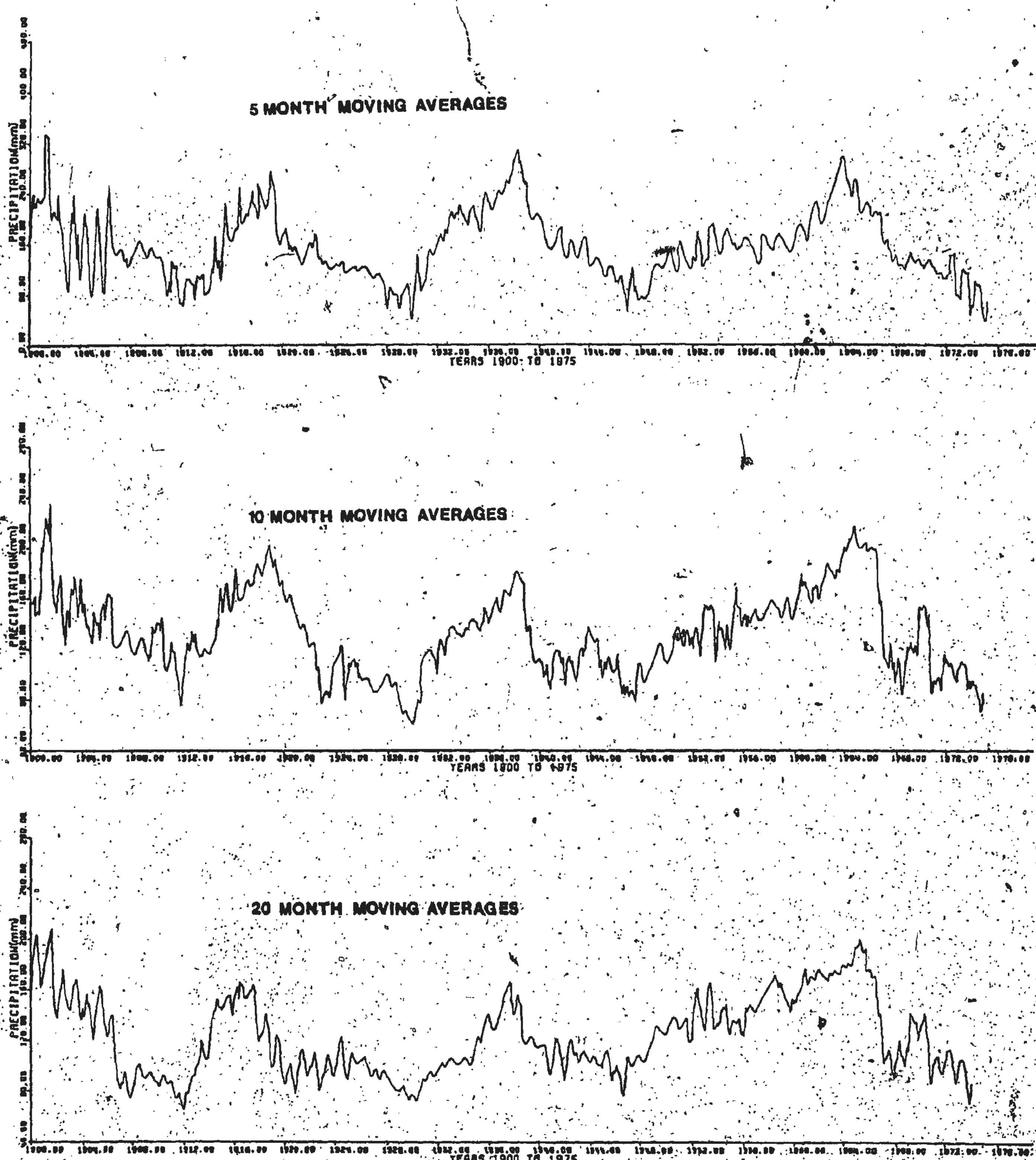
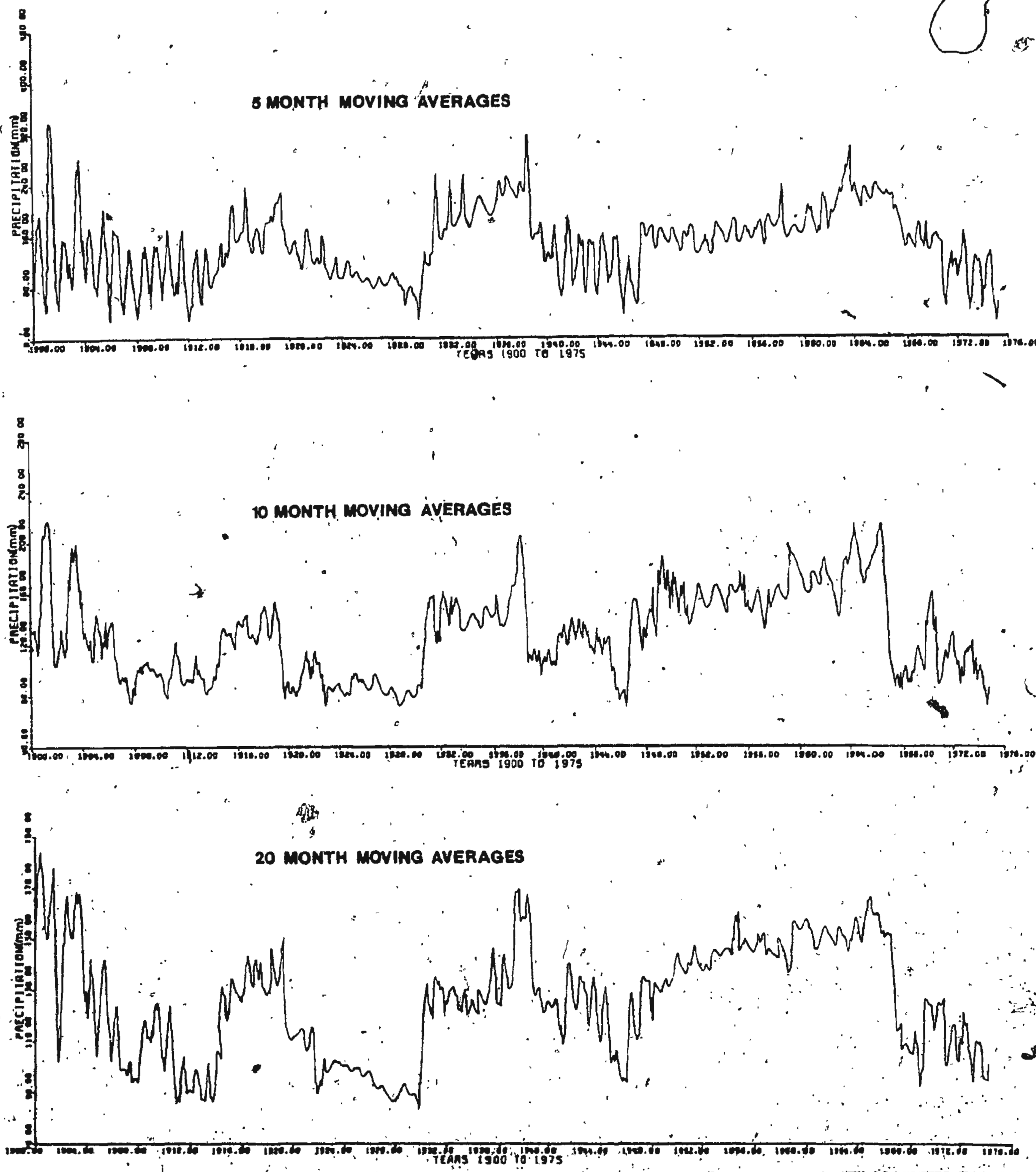


FIG 18(b)

HOLETOWN RAINFALL



at better than the 5% level. However, just as in the case of the mean island data the difference between the sample means for the periods 1931-38 and 1939-46 were statistically insignificant, falling near the 10% level of accpetance (see tables 6(a) and 6(b)).

Similarly, the two stations located in the south-easterly quadrant of the island, Searles and District 'C' and Central Station to the south-west exhibit much the same pattern in their regime. Between 1900 and 1908 there was a slow decrease in rainfall after which there was a significant increase until 1916. During the period 1916-30, a major downward trend set in but an upward fluctuation followed and lasted until around 1944. This latter fluctuation therefore, continued for some six years longer than it did at the west coast stations. At the same time, the ensuing period of lower rainfall, which only lasted for about seven years at stations in the west, tended to be more pronounced at District 'C', Searles and Central, spanning a period of some thirteen years. In other words, this trend started in the mid 1940's and ended around 1957. But whereas a marked increase in rainfall was recorded for nearly two decades (1947-65) at the two west coast stations, this upward fluctuation was delayed and lasted for only about eight years at Searles, District'C' and Central stations (circa 1958-1965). The final period of rainfall fluctuation identified, that is from 1965-75, seems to have coincided almost exactly at all seven locations (see figs. 18(a)-18(g)). The difference between the mean monthly rainfall values for selected fluctuation periods were also compared and tested for significance. It was discovered that at Searles, District'C' and Central, the differences between all pairs of

Table 6(a)

Significance Levels for Differences Between Sample Means* for Selected Periods - Holetown Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	t	Significance level
1900-13	1914-19	1395.3	1465.1	1.72	.05
1914-19	1920-30	1465.1	1197.8	2.86	.005
1920-30	1931-38	1197.8	1507.4	2.57	.01
1931-38	1939-46	1507.4	1470.5	1.32	.10
1939-46	1947-65	1470.5	1543.4	2.10	.025
1947-65	1966-75	1543.4	1460.0	2.45	.01

Table 6(b)

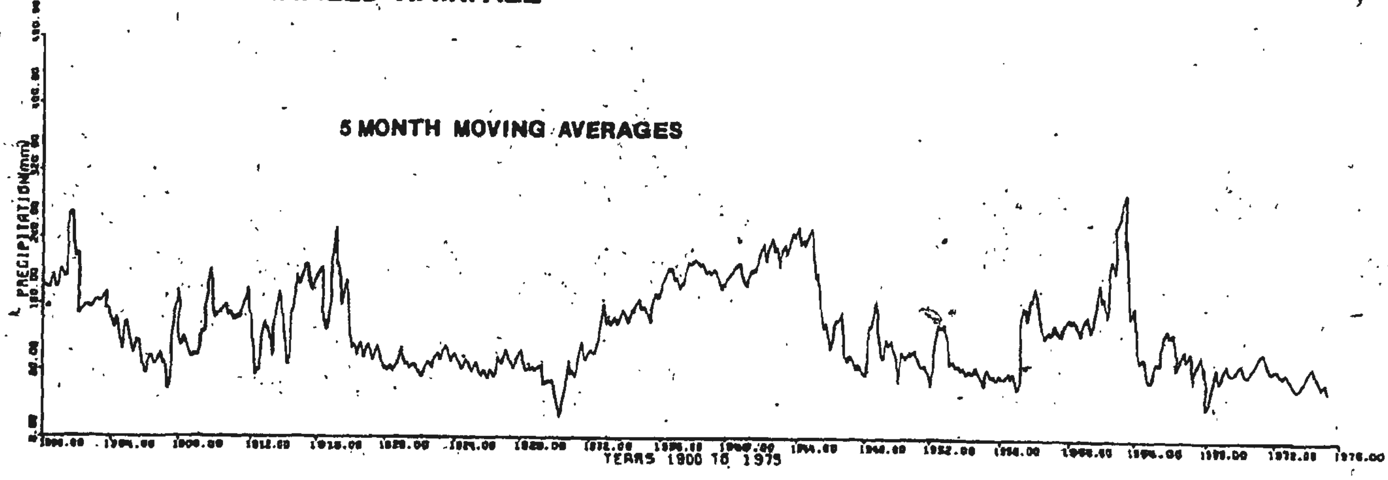
Significance Levels for Differences Between Sample Means* for Selected Periods - District "E" Rainfall

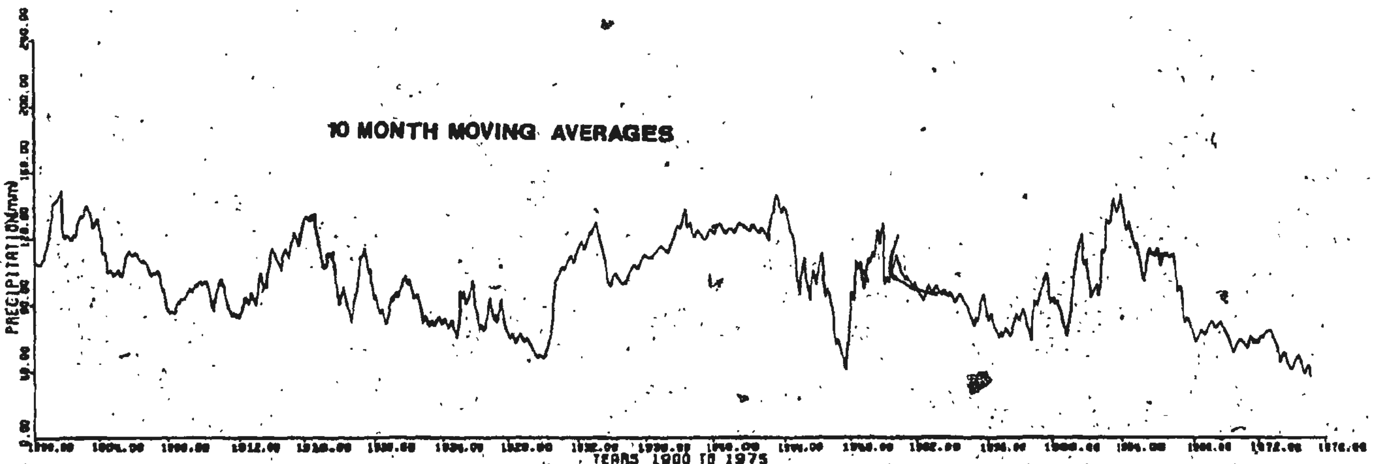
Periods of Fluctuation a	b	Sample Means (mm) a	b	t	Significance level
1900-13	1914-19	1620.1	1693.3	2.47	.01
1914-19	1920-30	1693.3	1421.2	2.45	.015
1920-30	1931-38	1421.2	1714.6	2.51	.01
1931-38	1939-46	1714.6	1674.4	1.27	.10
1939-46	1947-65	1674.4	1746.5	2.05	.025
1947-65	1966-75	1746.5	1665.0	1.68	.05

*Actual mean values for each fluctuation period.

FIG 18(c)

SEARLES RAINFALL





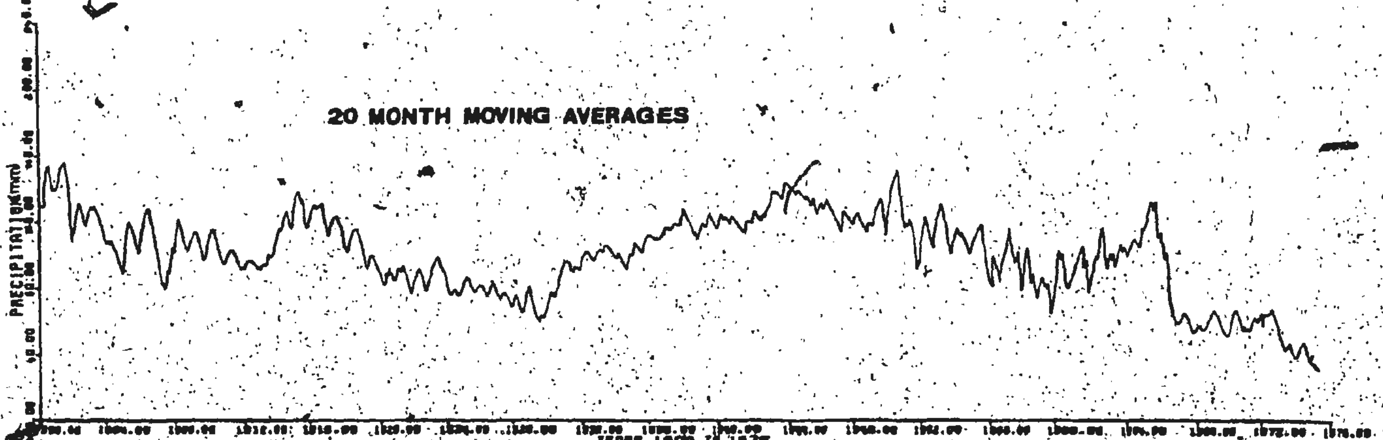


FIG 18(d)

DISTRICT 'C' RAINFALL

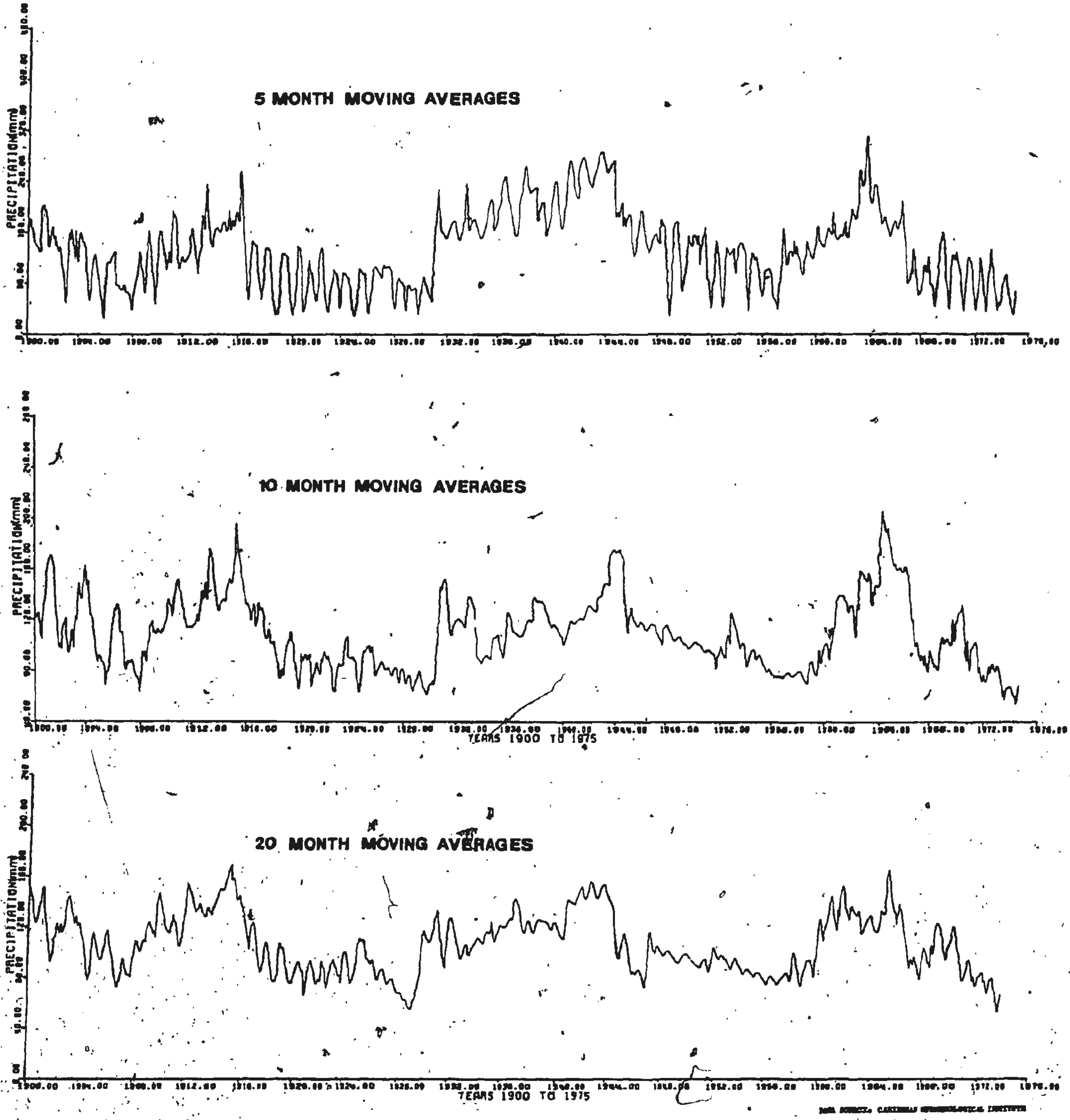


FIG 18(e)

CENTRAL RAINFALL

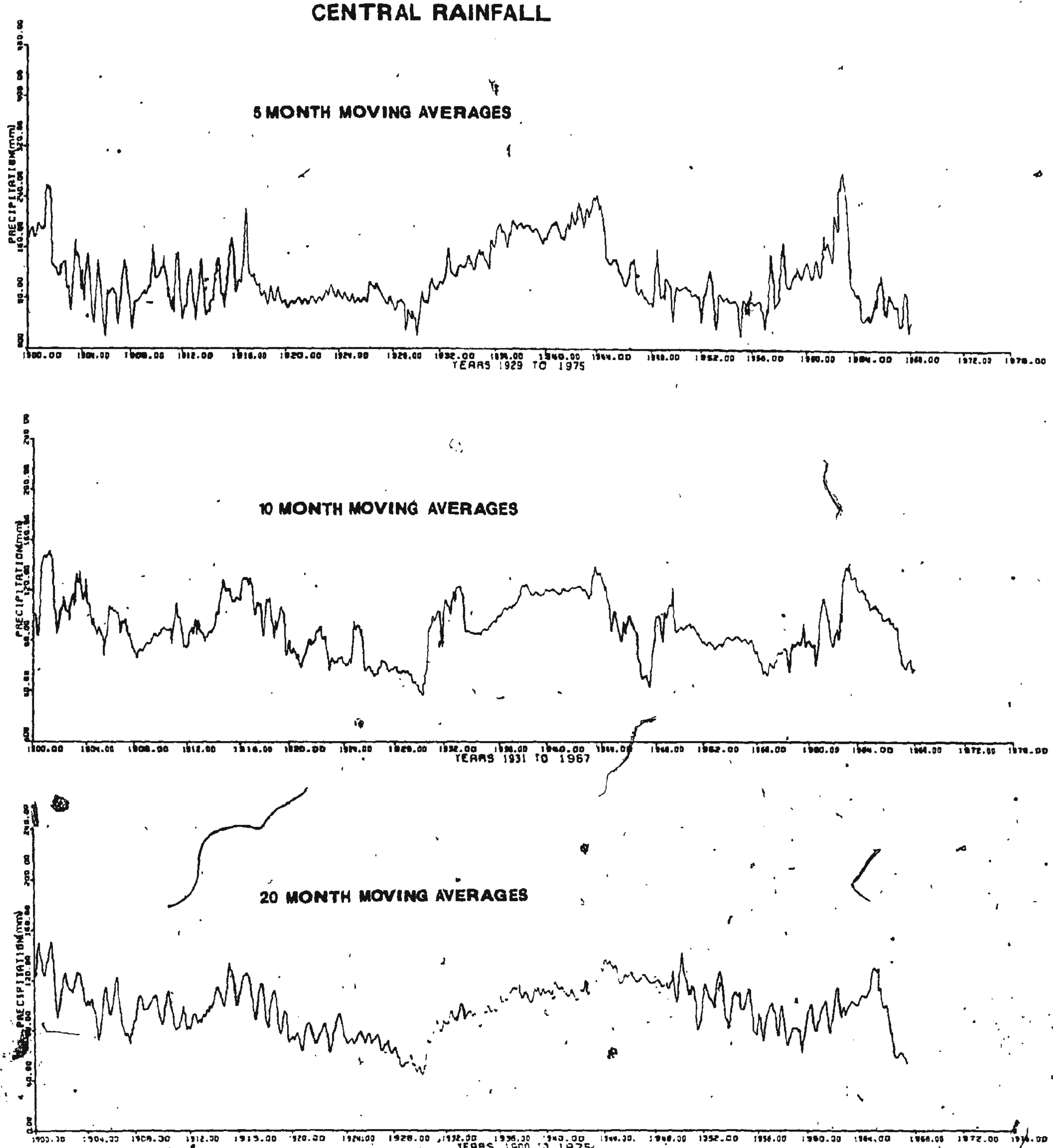


FIG 18(f)

LION CASTLE RAINFALL

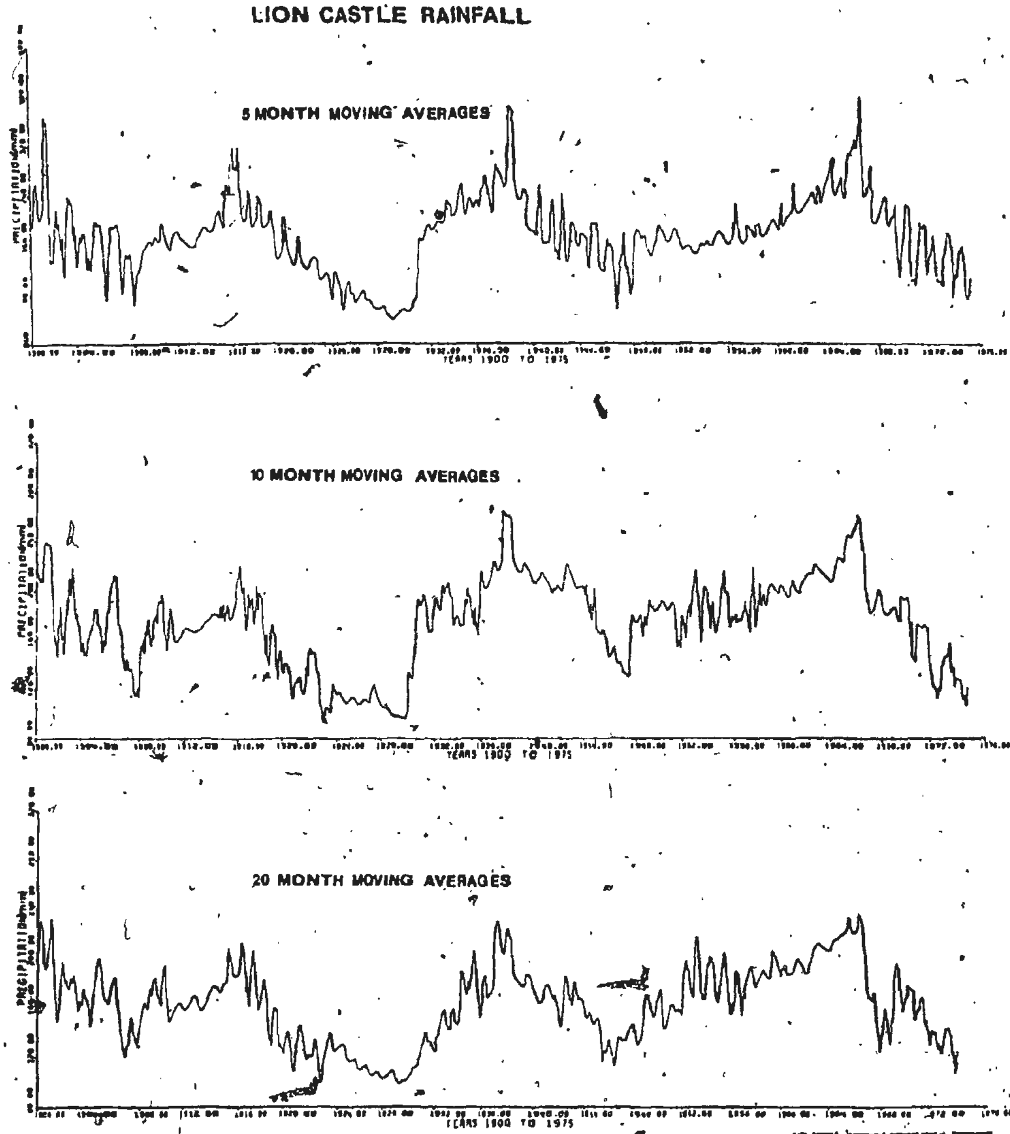
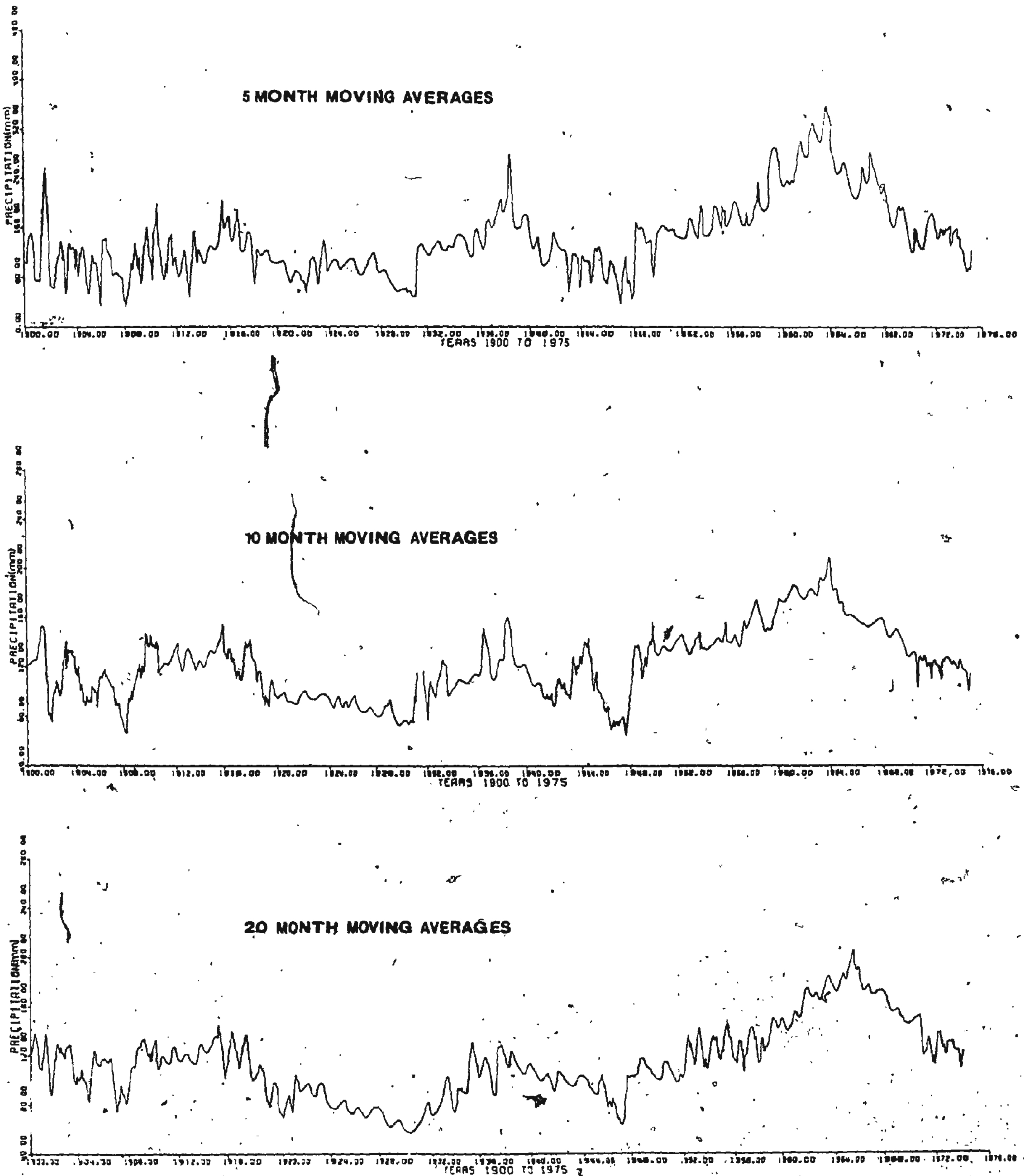


FIG 18(g)

DISTRICT F RAINFALL



sample means tested were significant at generally better that the 5% level (see tables 7(a), 7(b) and 7(c)).

It appears that the rainfall at the two stations in the south-east along with Central to the south-west tended to fluctuate at a more rapid rate than in the west. For instance, this is indicated by the fact that during the years 1909 to 1916 the mean monthly rainfall was approximately 12 per cent and 23 per cent more than during the periods 1900-1908 and 1917-30, respectively. (Compare this with 5 per cent and 19 per cent, respectively, for roughly corresponding periods at the two western stations.) As a further example, the mean rainfall recorded during the years 1958-65 at Searles, District 'C' and Central was almost 26 per cent and 10 per cent more than what was recorded in the respective periods 1917-30 and 1965-75. (Again, compare these figures with approximately 22 per cent and 6 per cent for roughly similar fluctuation periods at Holetown and District 'E'.)

The temporal rainfall regime exhibited by the two highland stations, Lion Castle and District 'F', presents a rather interesting case. Rainfall at the two stations, both at over 270 metres elevation, generally fluctuated in harmony with the south-easterly stations and Central up until about 1930. However, after this period the *timing* of each subsequent fluctuation coincided almost exactly with variations observed at the two west coast stations. At the same time, it should be pointed out that throughout the entire data period, the relative rate of change of each fluctuation appeared to be somewhat similar to those observed at

Table 7(a)

Significance Levels for Differences Between Sample Means* for Selected Periods - Searles Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	*t*	Significance level
1900-08	1909-16	1257.6	1416.9	2.56	.01
1909-16	1917-30	1416.9	1085.5	2.79	.005
1917-30	1931-44	1085.5	1240.1	2.45	.01
1931-44	1945-57	1240.0	1234.0	1.71	.05
1945-57	1958-65	1234.0	1475.1	2.51	.01
1958-65	1966-75	1475.1	1332.5	2.54	.01

Table 7(b)

Significance Levels for Differences Between Sample Means* for Selected Periods - District "C" Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	*t*	Significance level
1900-08	1909-16	1259.3	1417.1	1.69	.05
1909-16	1917-30	1417.1	1088.4	2.83	.005
1917-30	1931-44	1088.4	1243.7	2.45	.01
1931-44	1945-57	1243.7	1237.5	2.05	.025
1945-57	1958-65	1237.5	1478.0	1.73	.05
1958-65	1966-75	1478.0	1336.1	2.51	.01

Table 7(c)

Significance Levels for Differences Between Sample Means* for Selected Periods - Central Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	*t*	Significance level
1900-08	1909-16	1120.1	1278.4	1.72	.05
1909-16	1917-30	1278.4	951.0	2.80	.005
1917-30	1931-44	951.0	1110.6	1.67	.05
1931-44	1945-57	1110.6	1104.3	2.51	.01
1945-57	1958-65	1104.3	1340.4	2.08	.025

*Actual mean values for each fluctuation period.

District 'E' and Holetown, to the west. For instance, mean monthly rainfall during the period 1909-16 was approximately 5 per cent more than that for 1900-1908 and 17 per cent greater than the 1917-30 mean. Similarly, the mean fainfall in the years 1917-30 and 1965-75 was about 20 per cent and 8 per cent less, respectively, than the 1947-75 average. As in the case of all previous rainfall data sequences analysed, the difference between succeeding pairs of sample means was tested for statistical significance. Results indicate that for the most part these mean values were significantly differenct at better than the 5% level. Once more, the outstanding exception was the difference between the means of the fluctuation periods 1931-38 and 1939-46; in this instance the t values (1.37 and 1.31) could not be accepted as statistically significant at higher than the 10% confidence level (see tables 8(a) and 8(b)).

Integral-difference curves were also plotted for mean annual rainfall at the seven stations and the graphs analysed for long-term fluctuations. Generally, these curves portray much the same types of fluctuations as those exemplified by the moving averages. This again is further confirmation of the real existence of the temporal and spatial pattern in the island's rainfall regime discussed above (see figs. 19(a)-19(c)).

The spatial variations which have emerged from the analysis of the island's past rainfall regime are, to a great extent, in correspondence with the pattern of variability established in chapter 1. It may be recalled that the rainfall at stations of higher elevation and generally at stations which record high annual totals, tends to fluctuate less rapidly

Table 8(a)

Significance Levels for Differences Between Sample Means*for Selected Periods - Lion Castle Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	*t*	Significance level
1900-08	1909-16	2099.4	2269.2	1.74	.05
1909-16	1917-30	2269.2	1901.9	2.50	.01
1917-30	1931-38	1901.9	2211.5	1.68	.05
1931-38	1939-46	2211.5	2174.6	1.37	.10
1939-46	1947-65	2174.6	2247.5	2.44	.01
1947-65	1966-75	2247.5	2164.1	1.67	.05

Table 8(b)

Significance Levels for Differences Between Sample Means*for Selected Periods - District "F" Rainfall

Periods of Fluctuation a	b	Sample Means (mm) a	b	*t*	Significance level
1900-08	1909-16	1338.0	1507.8	1.72	.05
1909-16	1917-30	1507.8	1140.4	2.80	.005
1917-30	1931-38	1140.4	1450.0	2.05	.025
1931-38	1939-46	1450.0	1413.1	1.31	.10
1939-46	1947-65	1413.1	1486.0	2.46	.01
1947-65	1966-75	1486.0	1402.6	2.50	.01

*Actual mean values for each fluctuation period.

FIG. 19(a)

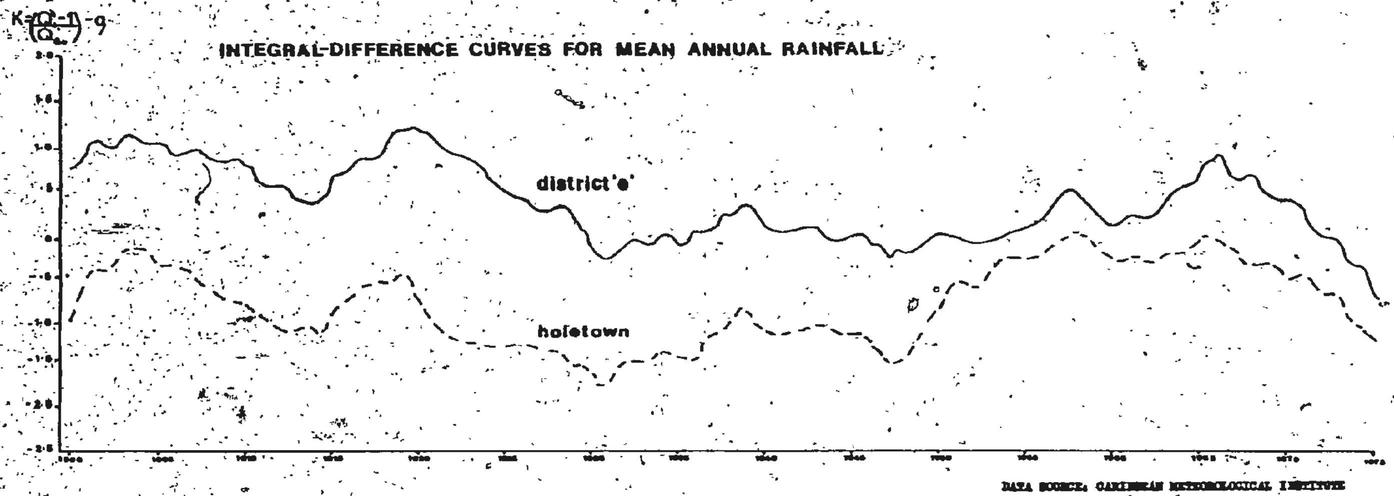
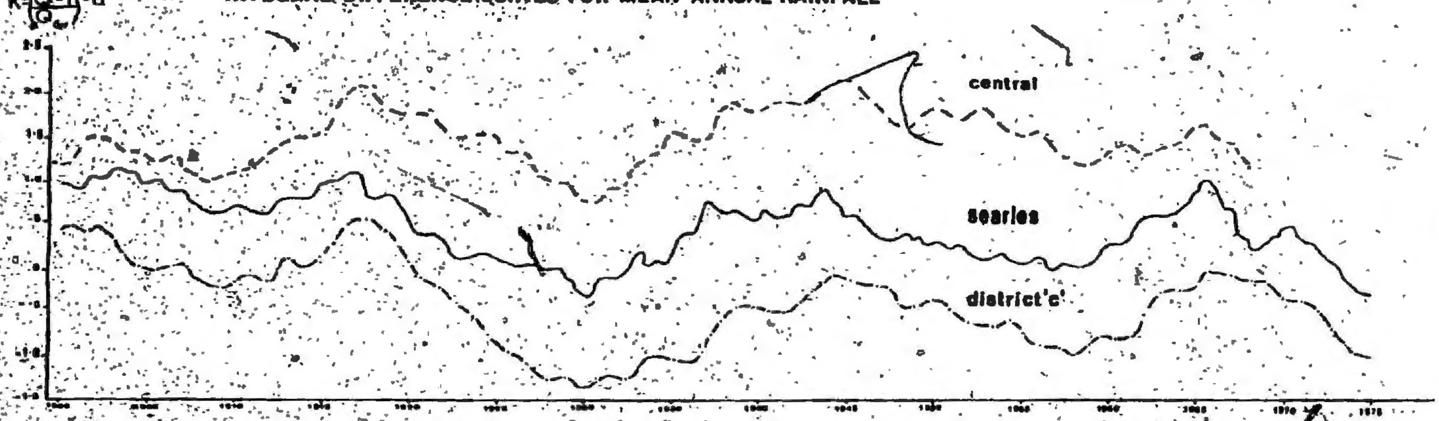

INTEGRAL-DIFFERENCE CURVES FOR MEAN ANNUAL RAINFALL
district'e'
holetown
DATA SOURCE: CARIBBEAN METEOROLOGICAL INSTITUTE

FIG. 19(b)

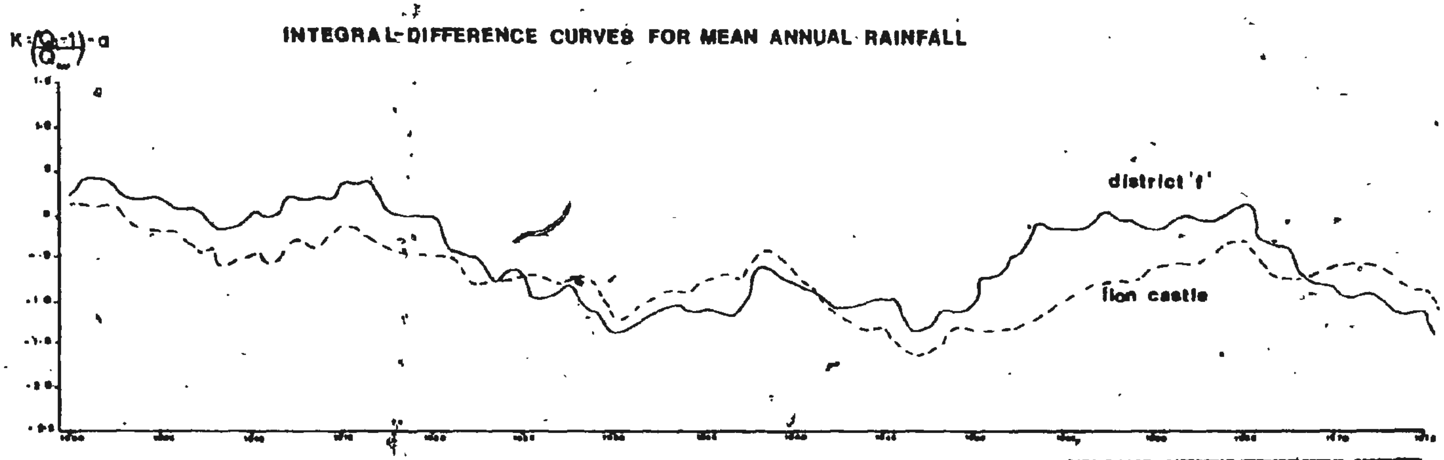
INTEGRAL-DIFFERENCE CURVES FOR MEAN ANNUAL RAINFALL



DATA SOURCE: METEOROLOGICAL OFFICE, NAIROBI

FIG. 19(c)

INTEGRAL-DIFFERENCE CURVES FOR MEAN ANNUAL RAINFALL



DATA SOURCE: CARIBBEAN METEOROLOGICAL INSTITUTE

than in low rainfall zones. This is substantiated by higher indices of the coefficient of variation in areas of generally low elevation and low mean annual rainfall. (Refer to table 2, p. 15)

It seems very significant that the two periods of lowest rainfall in the island's recent climatic past have coincided almost exactly at every location. During the years 1917-30 rainfall decreased rapidly to a "record minimum"; the mean rainfall for that period varied between approximately 951.0-1901.9 mm. During the other period of low rainfall, 1966-75, which was in phase at all stations mean values of between 1332.5 -2164.1 mm. were recorded. So far there has been little evidence to indicate a reversal of this recent trend and, in fact, it has even been suggested by some researchers that the trend may be intensifying in the tropics. Lloyd has shown that there has been a general decline in rainfall in Chile since 1944; but he demonstrated, however, that the trend has intensified rapidly from the 1960's to the present, causing widespread drought.[62] Recent research findings in other areas of the tropics also indicate a marked decrease in rainfall since the 1960's. In Jamaica for example, drought has occurred in some part of the island almost every year since 1963; and the Meteorological Service there reported at least a 10 per cent decrease in rainfall between 1963 and 1973[63]. Similarly Winstanley has demonstrated that there was a significant decline in rainfall in the Sahel zone south of the Sahara and in north-west India, since

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[62] Lloyd, op. cit., pp. 53-70.

[63] The Climate of Jamaica, op. cit., pp. 708.

about 1960.[64] He produced evidence to show that during the 1960's there was an expansion of the circumpolar vortex whereas the tropical meridional circulation contracted. This latter contraction was held responsible for the downward trend in rainfall and the recent severe droughts experienced.[65]

It has been further postulated that the recent dry phase might be "global" in extent and not necessarily confined to the tropics. For instance, Lamb contends that the decrease in rainfall is related to a change of the general wind circulation affecting most parts of the world. He postulates a weakening of the zonal westerlies in both hemispheres as well as a weakening of the North-Atlantic trades.[66] Hence, any further decrease in circulation intensity would almost certainly be reflected in decreased rainfall totals.

C. Application of Canonical Correlation

The variations observed in the long-term fluctuations of the seven sample stations seem to be closely related to the pattern of relationships described by the canonical variates computed for rainfall and weather variables. Table 9 shows the results of the canonical corrleation analysis

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[64] Winstanley, D., "Rainfall Patterns and the General Atmospheric Circulation", Nature, 245, 1973, pp. 190-194.

[65] This assertion of Winstanley's has recently been challenged by four researchers. See "Rainfall Trends in the West African Sahel" by Bunting, A.H., Dennett, M.S., Elson, J. and Milford, J.R. in Quart. Journal Royal Meteorological Society 102, 1976, pp. 59-64,

[66] Lamb, H.H., "Climate in the 1960's" Geographical Journal, 132, Part 2, 1966, p. 210.

TABLE 9

Results of Canonical Correlation Analysis Between

Seven Rainfall Variables and Six Weather Variables*

		R_c	Signif. Level	R_c	Signif. Level	R_c	Signif. Level
		0.77460	.005	0.54695	.01	0.33695	.05
	Variable	Coefficients for Canonical Variables of the First Set					
District "C"	1	-0.01945		-0.39541		-0.42037	
District "E"	2	0.34742		-0.14175		0.08386	
District "F"	3	-0.24157		0.41257		0.02413	
Central	4	-0.28154		-0.16412		-0.25561	
Holetown	5	0.41238		-0.13128		0.09385	
Lion Castle	6	0.37615		0.00931		0.10014	
Searles	7	-0.06901		-0.02148		-0.46351	
	Variable	Coefficients for Canonical Variables of the Second Set					
Temperature	8	0.19616		-0.06853		0.61157	
Pressure	9	0.18746		-0.20941		0.45421	
Wind Speed	10	-0.48324		0.58165		0.22485	
Rel. Humidity	11	0.46741		0.37149		-0.35268	
Sunshine	12	0.52335		-0.40332		0.09638	
Cloud	13	0.10708		0.88501		-0.34049	

* Λ, χ^2 and corresponding probability values were not available from the program.

performed on these variables. Altogether, the computer print-out produced six canonical coefficients (R_c) along with the associated canonical variates describing the overall variation in the data; but of these the first three coefficients are significant at the 0.5, 1.0 and 5% levels respectively. They describe most of the overall variance and also the strongest and most significant relationships between the two sets of data. Hence, only these three relationships are reproduced in the table. This analysis was performed as a further means of understanding the nature of long-term rainfall fluctuations at different locations on the island (see Chapter 2).

Results indicate that at Holetown, District 'E' and Lion Castle Stations, a combination of high temperature (+0.19), high sunshine (+0.52) and low wind speed (-0.48), along with high relative humidity (+0.46), is strongly associated with relatively high rainfall totals (+0.41, +0.34 and +0.37) for Holetown, District 'E' and Lion Castle, respectively. It may be recalled that the former two stations exhibited virtually identical fluctuations in their temporal rainfall regimes; therefore, it is not at all surprising to find the same combination of weather variables associated with rainfall variations at these stations. But the fact that the variation in Lion Castle rainfall is associated with these same weather variables does appear a bit conflicting at first. It might normally be expected that rainfall variations at this station should be associated with the same combination of variables as at District 'F'. This is not an unreasonable supposition especially considering that temporal fluctuations in rainfall have been in close phase at these two highland stations since

1900. However, Skeete has shown that the same combination of weather variables which describes the first relationship are also responsible for triggering the development of local convectional storms.[67] (This first relationship might be called the convective storm relationship.) These storms are experienced mainly in central, western and northern districts; and Lion Castle, like District 'E' and Holetown lie within these boundaries (see figure 19(d)). Hence, this could easily explain the apparent anomaly.

The second set of canonical variates suggests a strong correlation between high wind speeds (+0.58), high cloud amounts (+0.88), fairly high relative humidity (+0.37), and low sunshine (-0.40) and high rainfall (+0.41) at District 'F'. This combination of weather variables is apparently associated with low rainfall at most other stations. It seems fairly clear that the high rainfall at District 'F' is in large measure due to the "high wind" variable. This station is situated on the windward side of the northeast highlands whose longtitudinal axis runs approximately northwest to southeast. As a result, the area is exposed to the direct effects of the prevailing northeast trades which blow generally at right angles to the highland mass. This factor, coupled with the associated orographic effect is primarily responsible for the high rainfall totals recorded here. (This relationship can be referred to as the northeast trades - orographic relationship). Contrastingly, Lion Castle lies on the leeward side of this highland region, which further helps to explain

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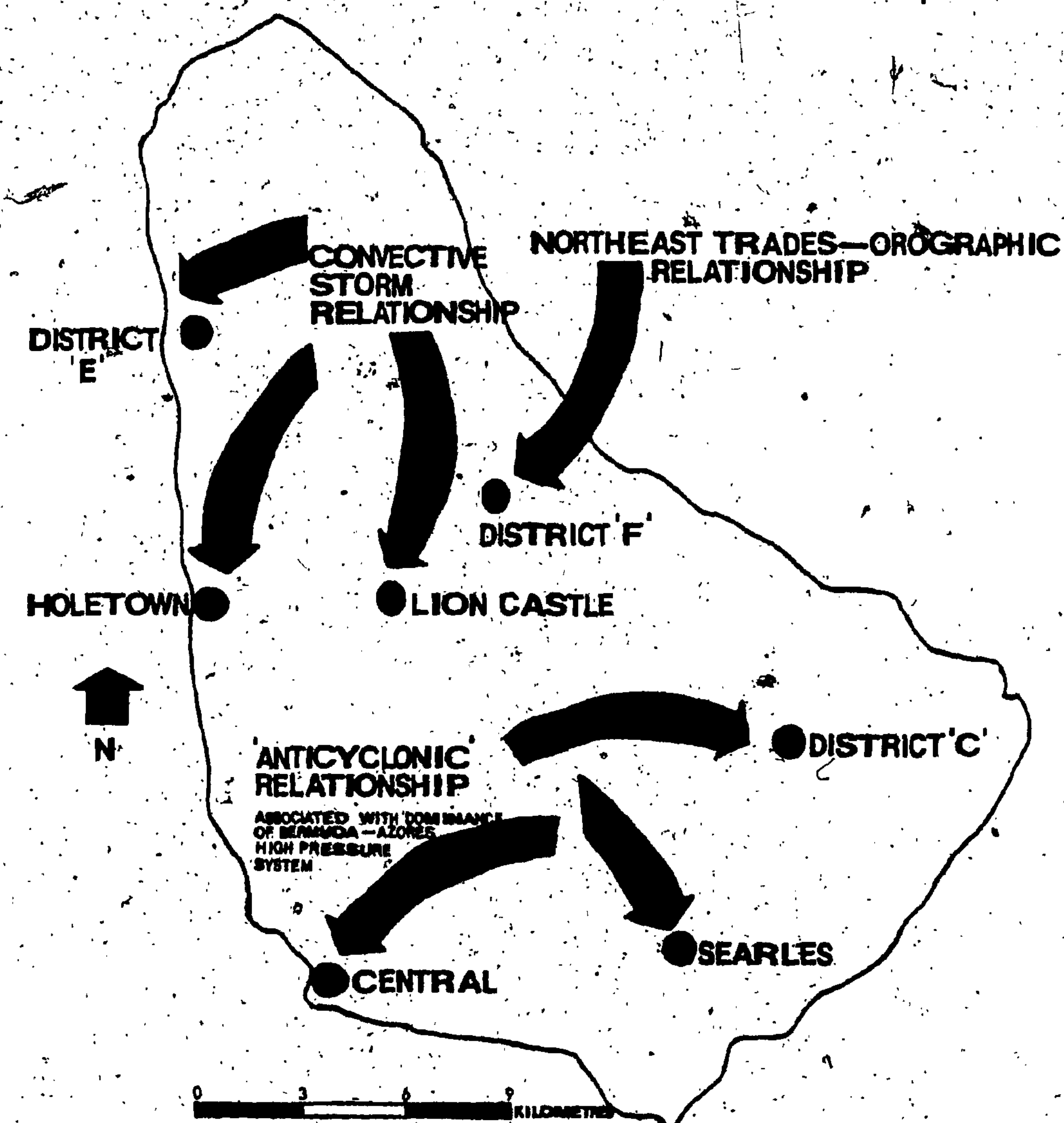
[67] Skeete, 1963, op. cit., p.4.

FIG. 19(d)

THE MAJOR RELATIONSHIPS DESCRIBED BY CANONICAL CORRELATION RESULTS



why most of the variance at this station is attributable to a different combination of factors.

Rainfall variation at Searles, District 'C' and Central stations is apparently related to a completely different combination of factors as indicated by the third set of canonical variates. Here there is a strong statistical relationship between low rainfall (-0.46, -0.42, -0.25 for Searles, District 'C' and Central, respectively) and high temperature (+0.61) high pressure (+0.45) and fairly high wind (+0.22) in combination with low relative humidity (-0.35) and low cloud (-0.34). Again, it should not be altogether surprising that most of the variance in rainfall at these three stations is attributable to an identical set of factors. For it might also be recalled that rainfall fluctuations at these stations have been almost identical throughout the entire period under study. This relationship might be due to the dominance of the Bermuda-Azores high, which gives rise to these "anticyclonic" conditions. (This relationship too may be called the Bermuda-Azores anticyclonic relationship).

Of the three relationships, the convective storm relationship (+0.77) is the most important, accounting for some 60% of the total variance of all factors. Similarly, the northeast trades-orographic relationship (+0.54) accounts for approximately 29% of the total variance; while the "anti-cyclonic" relationship is responsible for roughly 10% of the total variance.

D. Solar - Rainfall Relationships

In recent years, it has been suggested by several researchers that there is some association between sunspot activity and global rainfall fluctuations. Different types of relationships have been demonstrated between these two parameters, although the nature of these relationships is

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not wholly understood. For instance, in 1963, Baur discovered the existence of two peaks in Central Europe rainfall which he claimed to be associated with the two sunspot extremes.[68] More recently, Jagannathan and Bhalme found evidence of some correlation between Indian monsoon rains and solar cycles.[69] They found strong positive correlations in regions of orographic rainfall (especially the Himilayas), but generally, negative relationships in other areas. Another study has shown that there is significant statistical correlation between Addis Ababa rainfall and sunspot relative numbers.[70] It was discovered that between 1900 and 1970 rainfall peaks and troughs preceded sunspot maxima and minima by about 1.3 years on average. This relationship was found to remain relatively constant throughout the period.

In order to determine whether any such relationships existed between the Barbados rainfall data and sunspot activity, five year moving averages were plotted for mean annual rainfall and sunspot relative numbers 1900-60. Sunspot data were extracted from Waldmeier.[71] Hardly any consistent phase relationships can be established when figure 20 is examined. In some periods the fluctuations are completely out of phase while in others they are partly in phase; but overall they do not suggest any discernible

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[68] Baur, F., (1963) quoted in Lawrence, op. cit., p. 357.

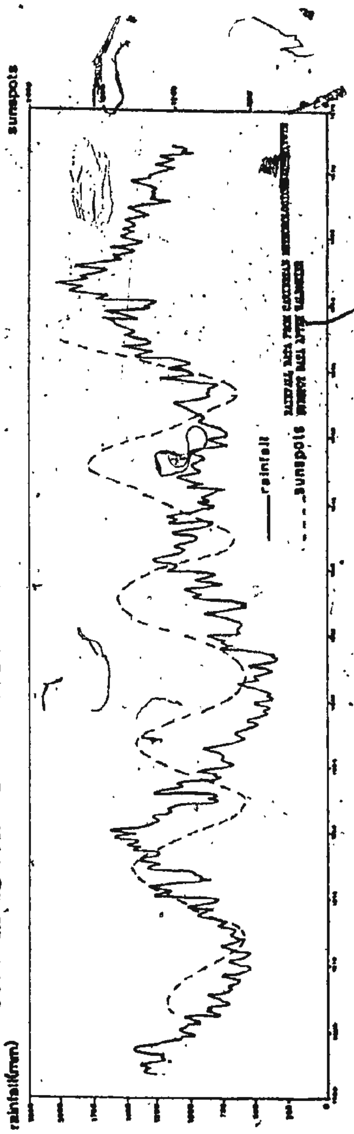
[69] Jagannathan, P. and Bhalme, H.N., "Changes in the Pattern of Distribution of Southwest Monsoon Rainfall over India Associated with Sunspots", Monthly Weather Review, 101, 1973, pp. 691-700.

[70] Wood, C.A. and Lovett, R.R., "Rainfall, Drought and the Solar Cycle", Nature, 251, 1974, p. 595.

[71] Waldmeier, op. cit., p. 110.

fig 20

5 YEAR MOVING AVERAGES FOR BARBADOS MEAN ANNUAL RAINFALL AND SUNSPOT NUMBERS



system of association. As a further test, the two variables were correlated statistically using the Product Moment Correlation Coefficient (r). The coefficient r = +0.08 was found to be barely significant at the 10% level. Hence, the null hypothesis that there is no significant statistical correlation between Barbados mean annual rainfall over the period 1900-1960 and sunspot relative numbers must be accepted.

However, this does not necessarily eliminate the possibility of there being an important physical association between these variables. The fact is that all relationships found between solar activity and terrestrial climate appear to be very complex; so that before any association can be firmly established, it would seem necessary to define the physical basis of such a relationship. Until such time as this is done, the real nature of such postulated relationships will still be largely a matter of speculation. Yet, for all this, there is little evidence to indicate any strong relationship between sunspot activity and rainfall fluctuations in Barbados.

E. Rain Days

Just as in the case of rainfall, there is considerable spatial variation in the annual number of rain days recorded over the island. The mean annual number of rain days varies from approximately 234 in high rainfall areas to 147 in regions of lower rainfall. Reliable data for total annual rain days for five of the seven rainfall stations were analysed for long-term variations. These data cover the period 1900-75 for District 'C', District 'E', District 'F' and Holetown stations but only up to 1968 for Central. Figures 21(a) - 21(c) show five and ten year

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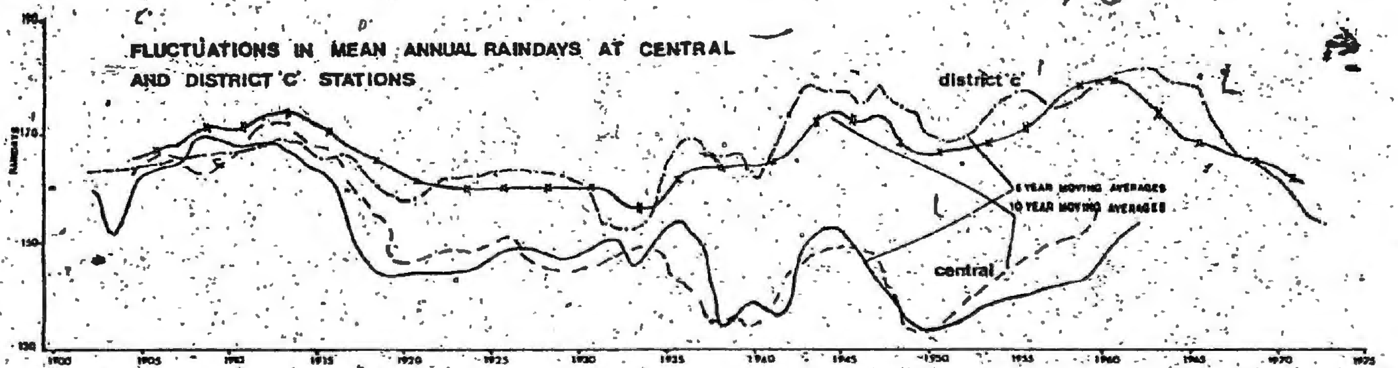
FIG. 21(a)



DATA SOURCE: METEOROLOGICAL OFFICE, [illegible]

FIG. 21(b)

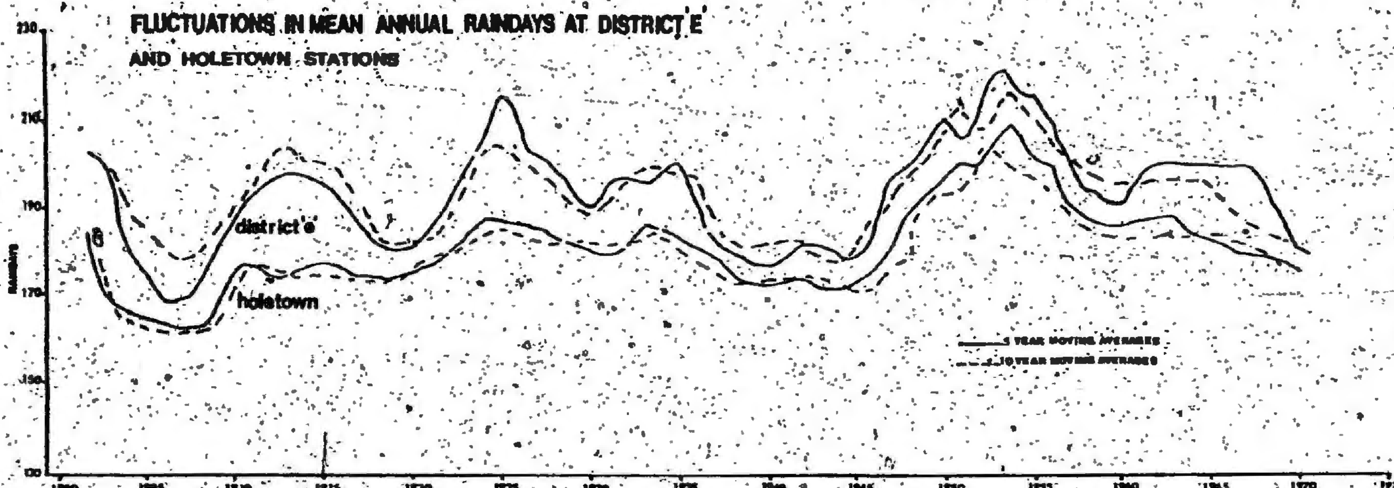
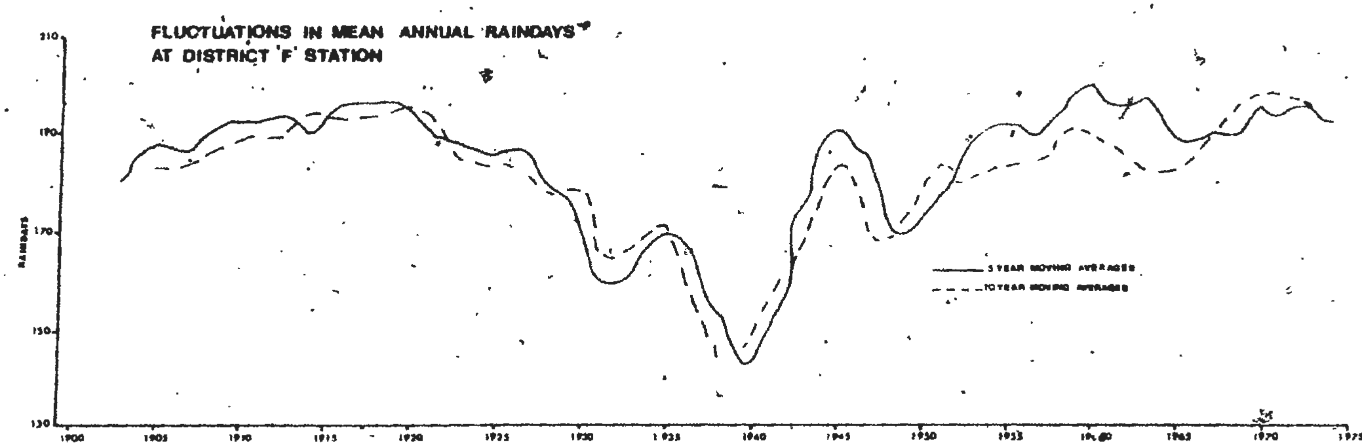

FLUCTUATIONS IN MEAN ANNUAL RAINDAYS AT DISTRICT E
AND HOLETOWN STATIONS
district e
holetown
Raindays
230
210
190
170
150
130
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975

FIG. 21(c)



DATA SOURCE: METEOROLOGICAL OFFICE, BRAKELL moving averages for total annual rain days at these locations.

It is significant that the pattern exhibited by Holetown and District 'E' on the west coast is almost identical, just as was the case with their rainfall regimes. Between 1900 and 1911 there was a gradual decrease in mean annual rain days but a reversal of this trend during the next decade or so. In fact, there was approximately 6 per cent more rain days in the 1911-20 decade than during the previous one. There was a slight decrease in rain days for about the next five years but a marked increase from 1925-30. For the next two decades up until 1950, there was a steady downward trend when the mean number of rain days was about 15 per cent less than in the previous half-decade. In the following decade there was a noticeable upward trend corresponding to an increase of roughly 18-20 per cent over the mean figure for the previous twenty years. From about 1960 to the present there has been another steady decrease in mean annual rain days at these two stations, the rate of decrease being roughly the same as during the period 1930-50.

Fluctuations in mean annual rain days at Central and District 'C' stations have also tended to be somewhat similar. Unlike the former two stations, there was a gradual increase in rain days at Central and District 'C' for about the first two decades after 1900. Thereafter, until the mid 1930's, a downward trend occurred; during this time the mean annual number of rain days decreased by some 10 per cent relative to the period 1900-19. From the 1930's to around 1947 mean rain days increased by approximately 13 per cent above the 1920-35 mean. From 1947 to about the

Table 10

Mean Annual Rain Days, Mean Annual Rainfall and Mean Rainfall Per Rain Day for Five Selected Stations

Station	Mean Rain Days	Mean Annual Rainfall (mm)	Mean Rainfall per Rain Day (mm)
Central	147	1136.7	7.7
District "C"	170	1293.2	7.6
District "E"	234	1651.5	7.0
District "F"	201	1391.9	7.2
Holetown	207	1436.8	6.9

Table 11

Product Moment Correlation Coefficients for Total Monthly Rain Days and Total Monthly Rainfall for Five Selected Stations *

Station	Correlation Coefficient (r)	Significance level
Central	.691	.005
District "C"	.612	.01
District "E"	.563	.01
District "F"	.564	.01
Holetown	.560	.01

*The two sets of data cover the period 1900-75, except in the case of Central Station whose data period ends at December 1968.

mid 1950's there was a slight decrease in rain days but a marked increase from then until the mid 1960's. There has been a downward fluctuation ever since the 1960's, which so far has exceeded the rate of decrease of the 1920-35 period.

Analysis of District 'F' data reveals that there were four major fluctuations over the period under study. There was a noticeable upward trend for the first two decades but then mean annual rain days decreased by approximately 15 per cent in the following two decades. From about 1939 to 1960 an upward trend set in corresponding to about a 20 per cent increase over the 1920-39 mean. Since 1960 however, no clear trend has emerged. Between 1960 and 1965 there appears to have been an overall decrease in the number of raindays at this station followed by a gradual increase over the next ten years.

It seems significant that although the patterns of fluctuation have varied from point to point both in terms of *timing* and direction, a notable decrease in rain days has been observed at all locations during the post-1960 period. It might be worth recalling that this period has also been one of decreasing rainfall at all stations. This is perhaps the only period that rainfall and rain day fluctuations have been in such close phase.

As might be expected stations which record the lowest rainfall totals tend to have the least rain days. This is clearly revealed in table 10 above, which lists the long-term mean of annual rain days for each of the five stations. However, at the same time it can be shown statistically that there is stronger correlation between rainfall and rain days in low

FIG 22(a)

RELATIONSHIP BETWEEN RAINFALL AND RAINDAYS AT THREE STATIONS

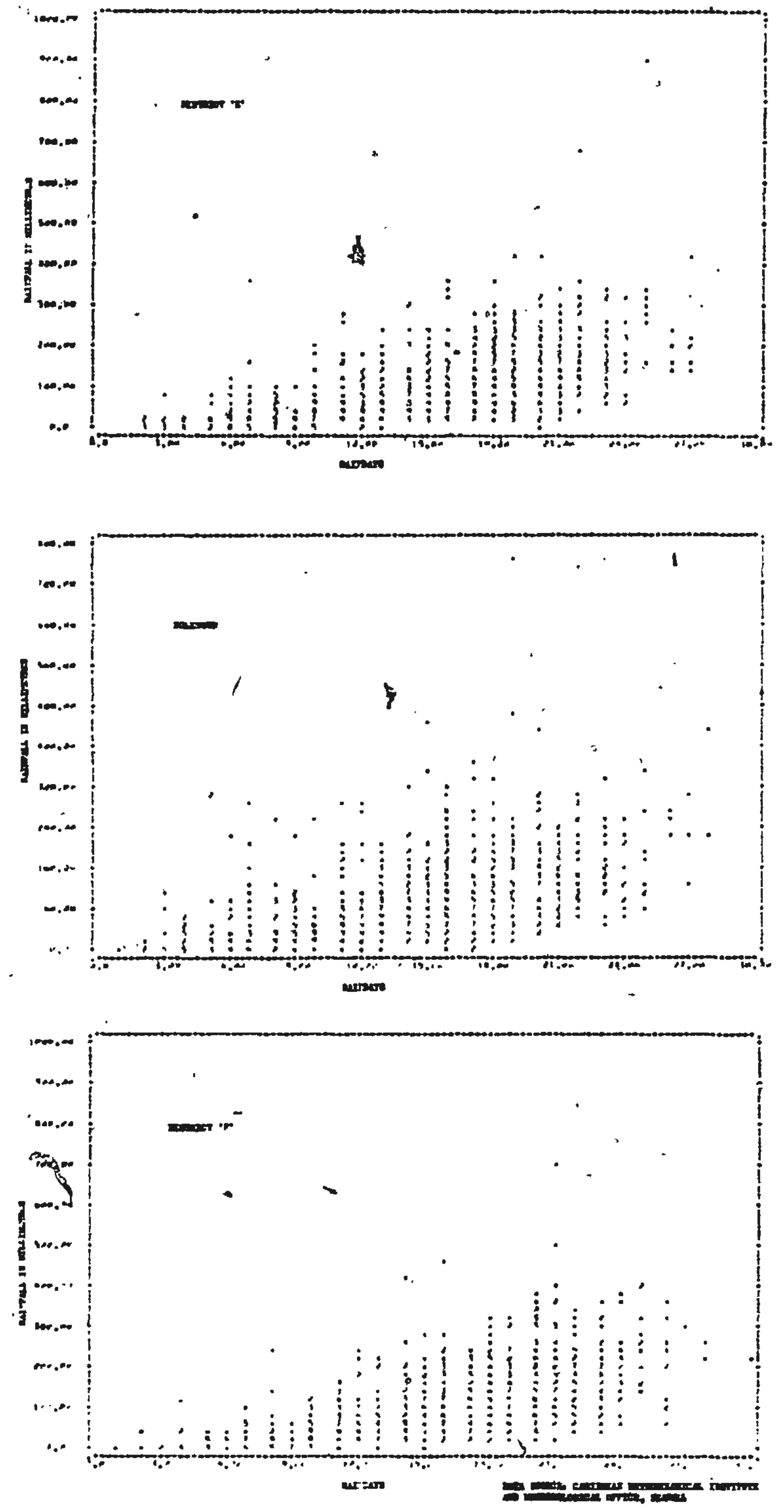
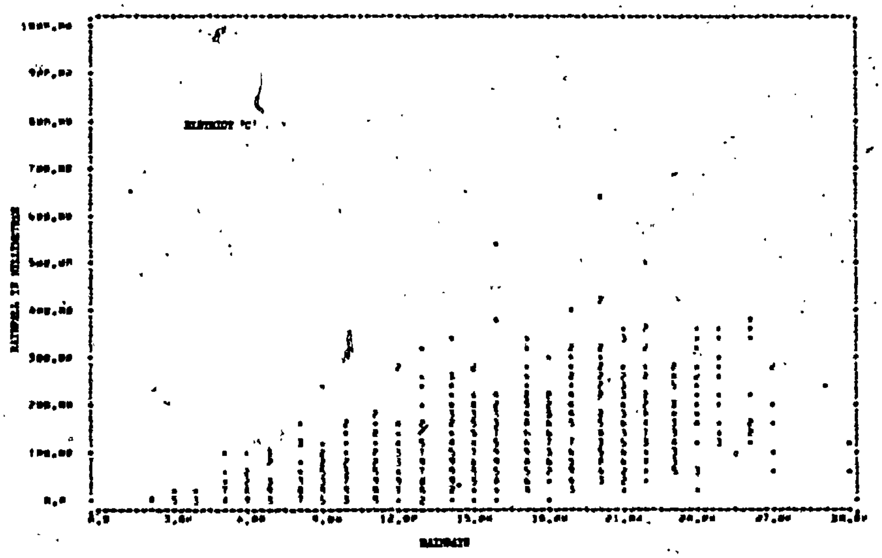
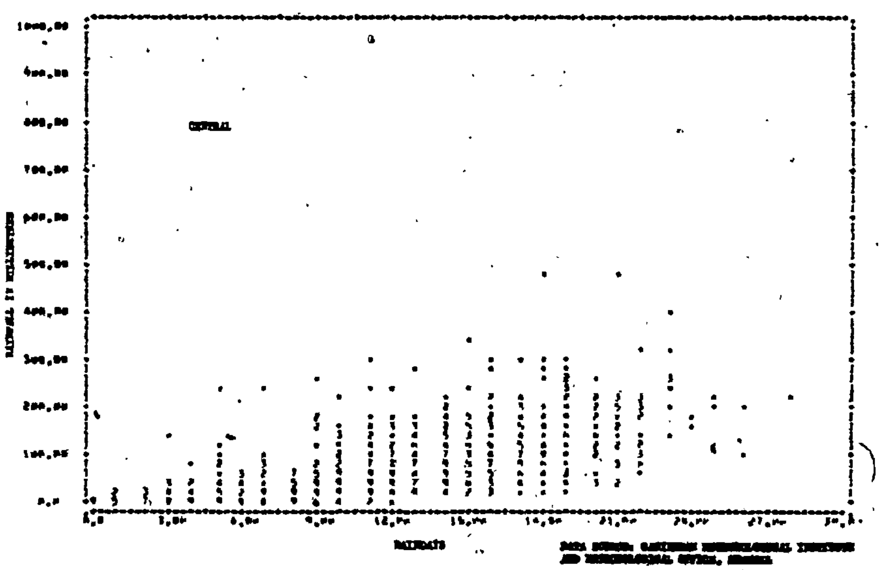


FIG 22(b)

RELATIONSHIP BETWEEN RAINFALL AND RAINDAYS AT TWO STATIONS





rainfall areas than in regions of higher rainfall. Table 11 is an extract from the computer print-out of the correlation coefficients between total monthly rainfall and total monthly rain days for each of the five stations. It can be seen, for instance, that the coefficient computed for District 'F', Holetown and District 'E' is approximately $r = 0.56$, whereas $r = 0.61$ and 0.69 for District 'C' and Central, respectively (see also the scattergrams in figures 22(a) and 22(b)). Further, although there are fewer rain days at Central and District 'C', these stations on the average, receive more rainfall per rain day than any of the other stations. Table 10 shows, for example, that mean rainfall per rain day varied from 6.9 mm - 7.2 mm at the three stations with the highest rainfall; but increased to approximately 7.6 mm and 7.7 mm per rain day at District 'C' and Central, respectively.

In summary, therefore, it is clear that the pattern of temporal fluctuations shown in the Barbados mean annual rainfall data may be taken as generally representative of most locations on the island. Despite the slight spatial variation demonstrated within this overall pattern, the temporal regimes at all stations appear to be broadly similar. This would tend to indicate that the entire island is dominated by similar broad-scale patterns of circulation, as for example in the case of atmospheric pressure and air motion. As a result, any major shift or interruption in this broad circulation pattern would be reflected in changes in a similar direction, though not necessarily of the same magnitude, at all locations.

Chapter 5

Fluctuation and Trends in Major Synoptic Systems

A. Classification of Weather Systems

There are a few synoptic scale systems which significantly affect the weather in Barbados. The most important synoptic systems which develop are incipient storms and hurricanes and local convectional systems. It is important to note that the major portion of these weather systems tend to develop during the latter part of the rainy season and normally account for around 68-72 per cent of the island's annual rainfall. Since these weather systems are such important features of the island's climate, an attempt will be made in this chapter to analyse fluctuations and changes in their frequency since 1900.

It should be made clear at this point that for purposes of this analysis, tropical storms and depressions will be analysed together as constituting a single type of synoptic system. This seems quite justified inasmuch as they all develop from similar synoptic conditions and are usually of virtually similar intensity. However, though of similar genesis, hurricanes will be treated separately. These are by far the most destructive type of weather disturbance which affect the island's weather and are normally associated with some of the heaviest rainfall totals recorded on the island. It should be emphasized, too, that the *centres* of these disturbances hardly ever traverse the island but usually pass a few miles offshore; primarily in directions varying between northeast and southeast. As a matter of fact, during the period 1900-1975 only one hurricane ('Janet' of September 1955) passed directly over the island. Hence, the weather systems being analysed have not necessarily traversed the island but rather are known to have significantly affected the island's weather at some stage in their cycle.

Barbados is indeed fortunate since the island lies outside the main Caribbean hurricane tracks. For instance, between 1730 and 1975 only five hurricane centres passed directly over the island, thereby giving a probability frequency of approximately .02 or one nearly every fifty years. The years of actual occurrence were 1731, 1780, 1831, 1898 and 1955, equivalent to periods of 50, 51, 67 and 57 years, respectively between occurrences.

Local convectional storms deserve special mention because of their peculiarly characteristic mode of formation. These systems are carefully described by Skeete[72] who found their chief characteristics to be their *extreme localisation*, their relatively small area of precipitation, their high precipitation rates and formation exclusively during daytime hours. At the same time, the main factors triggering their development appear to be high sunshine duration, high humidity conditions and low wind speeds. All the mechanics behind the formation of these systmes and all the physical processes involved are not fully understood but the actual mode of formation is fairly well known. The following statement extracted from the work of C.C. Skeete describes the sequence of events leading up to their formation.

> "Sunshine warms the lowest levels of the air: the heated air rises: the moisture of the air condenses in its cooler surroundings at higher levels to form cumulus cloud. This cumulus cloud drifts

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[72]Skeete, 1963, op. cit., p. 4.

slowly with the main air current and tends to amass on that side of the island opposite to the quarter from which the main current is moving. This process usually continues for about two or three hours ... by which time the conditions in the amassed cumulus cloud have reached the stage of precipitation. Rain begins to fall over a small area, usually not more than one or two square miles in extent. The cloud has now reached the cumulonimbus stage ...: heavy torrential rain falls over the original or closely adjoining area of development. Usually within one to one and a half hours after the beginning of precipitation the cumulonimbus develops into a temporary thunderstorm ..."[73]

These local convectional storms are normally so limited in their effect that only specific locations on the island are affected, mainly the central, northern and northwestern parts of the island. Again, it should be emphasized that although these storms are small in extent, they are capable of producing substantial amounts of rainfall in the areas where they occur.

B. Hurricanes

There seems to have been a fairly distinct pattern in the frequency of occurrence of hurricanes affecting Barbados in the past. During the first three decades of this study (i.e. from 1901-30) the number of hurricanes influencing the weather in each decade were six, four and three, respectively. In other words, there was a progressive decrease in hurricane activity in the area after 1901, culminating in the decade 1921-30 when the least number of hurricanes were recorded. It is significant that the decade 1921-30 was also known as a period of generally dry weather throughout most of the Caribbean. In fact, it has previously been shown that this was the driest period in the island's climatic history since 1900.

The number of hurricanes affecting islands in and around the vicinity

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[73] *Ibid*, p. 5.

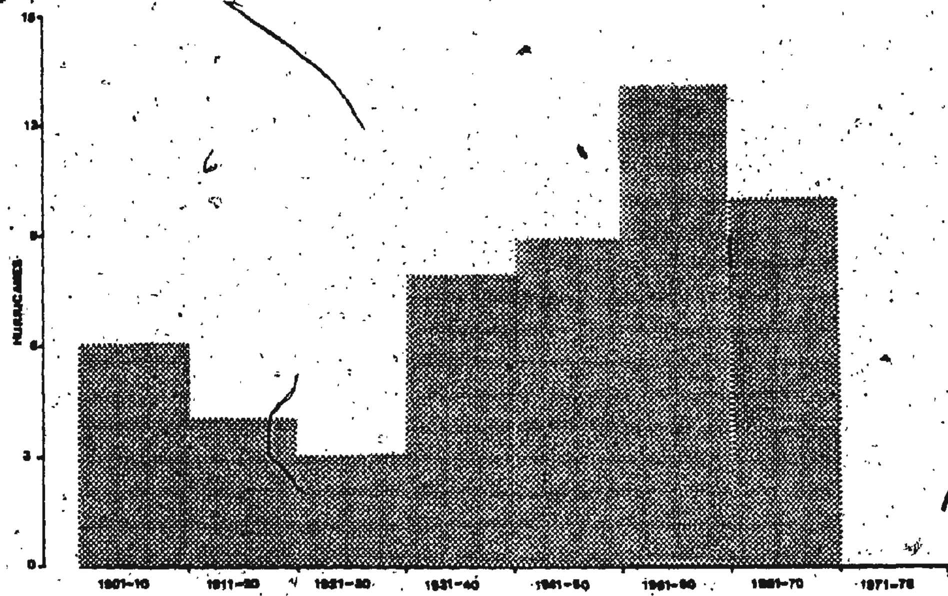
of Barbados showed a remarkable increase in the three successive decades 1931-60. During these decadal periods the number of hurricanes were eight, nine and thirteen, respectively. After this period, hurricane activity again decreased. In the decade 1961-70 there were ten hurricanes affecting weather conditions over Barbados, or roughly a decrease of 20 per cent relative to the previous decade. This apparent decrease in the incidence of hurricanes seems to have continued to the extent that so far in the present decade, commencing from 1971, no weather systems of hurricane intensity have affected weather conditions on the island. (see fig. 23).

These data suggest therefore, that there might be successively alternating periods of reduced and increased incidence of hurricanes affecting Barbados. In the present case, it appears that periods of length approximately three decades of low hurricane incidence alternate with similar periods of increased activity. Perhaps it might be a little early to state precisely whether or not this possible quasi-cyclical rhythm can be confidently used as a basis for prediction. It is unfortunate that there are no reliable data prior to 1901 which would enable further investigation of this apparent rhythm. But it should prove interesting to observe carefully the pattern which emerges in future decades.

It is also clear that generally there was a lower incidence of hurricanes in the first part of the present century than in later decades. Over the 76 year period for which data exist, there were fifty-three hurricanes recorded. However, of these only eighteen or roughly 33 per

FIG. 23

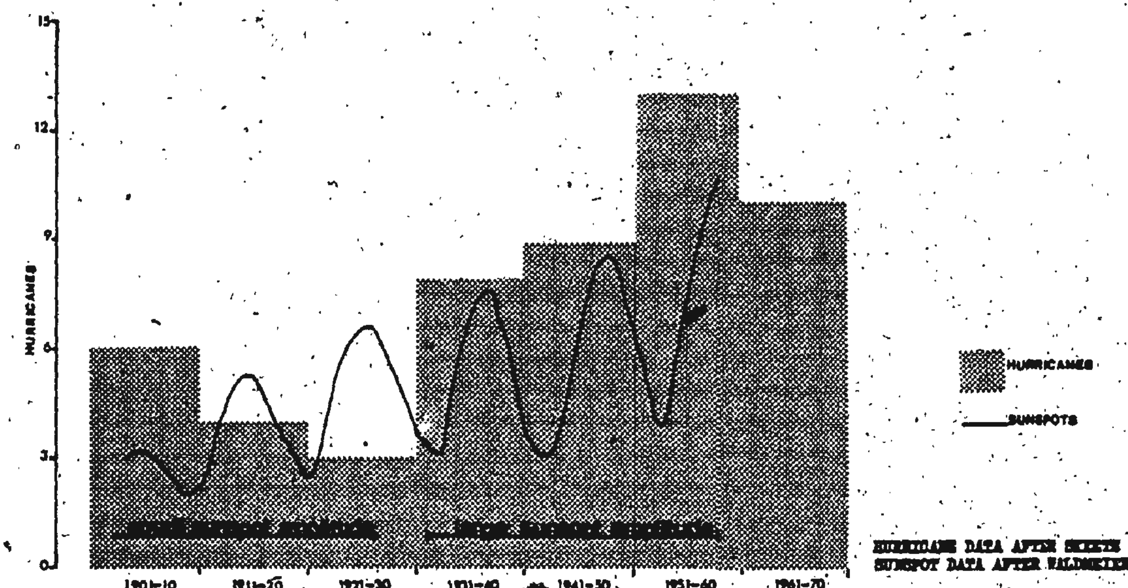
FREQUENCY DISTRIBUTION OF HURRICANES AFFECTING THE WEATHER IN BARBADOS



DATA AFTER SKEETE

FIG. 24

RELATIONSHIP BETWEEN HURRICANE FREQUENCY AND SUNSPOT AMPLITUDE



HURRICANE DATA AFTER SKEETE
SUNSPOT DATA AFTER WALDMEIER

cent occurred during the first half of the period. What is even more striking is the fact that more of these hurricanes occurred in the last 25 years than during the first 50 years of the century. In absolute terms there were twenty-six hurricanes recorded during the first 50 years after 1900, whereas 27 were recorded during the last two and a half decades covered by the data.

It is worth noting that the change in frequency of hurricanes has occurred in association with an apparent change in the general circulation of the atmosphere over the Northern Hemisphere. Both Dzerdzeevskii[74] and Kalnicky[75] have demonstrated that the Northern Hemispheric circulation changed from a more stable zonal flow between 1900 and 1950 to more vigorous meridional flow ever since then. The change in the incidence of hurricanes at the latitude of Barbados coincides almost exactly with these circulation changes. For during the period of relatively stable zonal hemispheric flow there was a very low incidence of hurricanes, whereas hurricane activity increased dramatically after 1950 with the tendency towards more vigorous meridional exchange.

However, no cause and effect relationship should necessarily be inferred simply because temporal changes in the atmospheric circulation and hurricane activity at Barbados have been in phase. This could be ill-advised at this stage in the light of the fact that neither the dynamics of the atmospheric circulation nor the mechanics of hurricane development are as yet fully understood. Yet, it is strongly believed that there is

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[74] Dzerdzeevskii, op. cit., pp. 285-292.

[75] Kalnicky, op. cit., pp. 100-112.

some important physical relationship between indices of circulation and surface weather systems. But the exact relationship will only be known as more research is undertaken.

Although no precise physical relationship can as yet be adduced there appears to be a fairly close association between sunspot amplitude and hurricane frequency at Barbados. Data for sunspot relative numbers were extracted from Waldmeier[76] and 5-yearly means plotted. The graph indicates that the period 1900 to approximately the late 1920's was one of relatively low sunspot amplitude, whereas the period from the mid 1920's to 1963 was one of markedly higher amplitude. When this graph is superimposed on the frequency histogram of hurricane frequency (fig. 24), the phase relationship becomes quite evident. For it is noticeable that periods of low sunspot relative numbers coincide with periods of reduced hurricane frequency and vice versa. Again, it should be emphasized that this does not suggest a cause and effect relationship; neither should it be inferred that the relationship holds good for the tropical North Atlantic - Caribbean region. The data on hurricane frequencies employed in the analysis only relate to those systems which have passed close enough to the island of Barbados to affect weather conditions there. Hence, the apparent association might simply be a chance relationship. What would be needed to establish the possible validity of such a relationship would be the correlation of sunspot relative numbers and the relative frequency of of North-Atlantic hurricanes over several decades.

It is important to note the vast majority of hurricanes affecting the weather at Barbados have occurred during the post 1930 period when

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[76] Waldmeier, <u>op. cit.</u>, pp. 100-110.

temperatures rose to what was believed to be their highest in the island's known climatic history. Empirical research has shown that in order for hurricanes to develop the surface temperature of the ocean over which they form must be at least 27.6°C. This is not the only condition necessary for hurricane formation, but for reasons not yet wholly understood, it is known to be a prime prerequisite.[77] Brown[78] has previously demonstrated that in the case of the tropical North Atlantic Ocean, sea-surface temperature fluctuations have been in perfect phase with air temperature fluctuations. In view of this and in the absence of reliable sea-surface temperature data, it was felt that the air temperature record would give a very reliable assessemnt of what oceanic temperatures were like.

Using the mean annual temperature graph in figure 6 as a basis therefore, it could safely be assumed that sea-surface temperatures in the Caribbean region (in the vicinity of Barbados) were consistently higher after the late 1930's than before. For whereas the mean annual temperature was generally below 26.2°C prior to the 1930's, it rose well above this mark, with minor fluctuations thereafter (see figure 6). Perhaps an even more accurate picture is portrayed when the temperature graph for August is analysed. August is easily one of the hottest months at most localities in the Caribbean and is also quite representative of temperature conditions during the normal hurricane season. If reference is made to figure 7, it becomes clear that mean August temperatures have been for the

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[77] Riehl, H., Tropical Meteorology, McGraw-Hill, 1954, p. 331.

[78] Brown, op. cit., p. 109-122.

most part in excess of 27°C after the 1930-40 period; before this data, however, temperatures scarcely ever reached this mean figure. Hence, on closer analysis, the low incidence of hurricanes in the first few decades of this century might be partially be explained.

It was felt that there might also be some evident correlation portrayed between the fluctuations in hurricane frequency and variations in atmospheric pressure. Since hurricanes are known to develop, at least initially, from centres of low pressure one might have expected a better relationship between figures 13 and 23. Unexpectedly, it appears, at least from the diagrams, that the earlier decades of lower pressure were also the period of lowest hurricane frequency. But this should not imply that some relationship does not exist; in fact, research has proven the existence of such a relationship.[79] What might be implied here is that although both parameters are important for hurricane development, the temperature variable might be more important initially than pressure.

C. Tropical Storms and Depressions

The frequency distribution of tropical storms and depressions shown in figure 25 does not present as readily identifiable a pattern as in the case of hurricanes. It is only in the first four decades from 1901 that a clear trend emerges. Between the years 1901 and 1940, there was a steady decadal increase in the number of tropical storms and depressions influencing the island's weather. The number rose from nine in the first decade, to eleven in the second, to twelve in the third, to twenty in the fourth decade since 1901. The high peak in tropical storm activity

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[79] Riehl, op. cit., pp. 284-286.

Fig. 25

FREQUENCY DISTRIBUTION OF TROPICAL STORMS AND DEPRESSIONS AFFECTING THE WEATHER IN BARBADOS

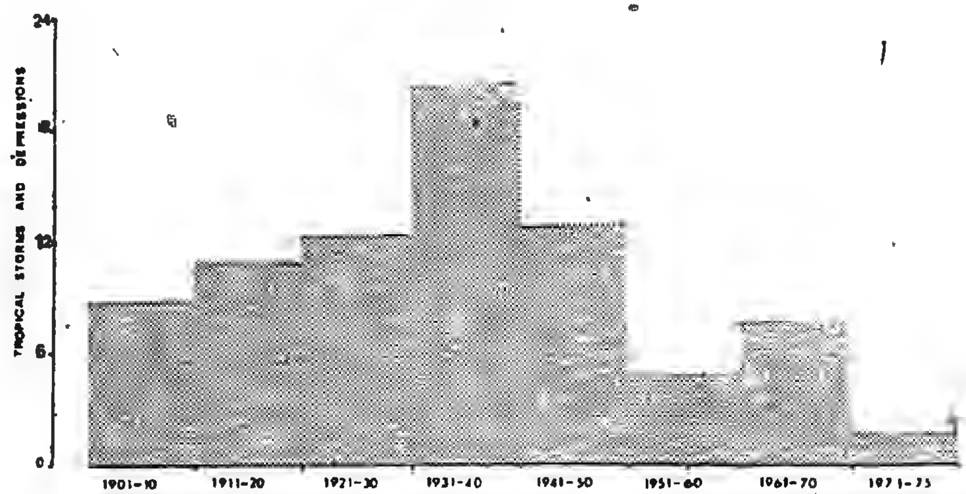
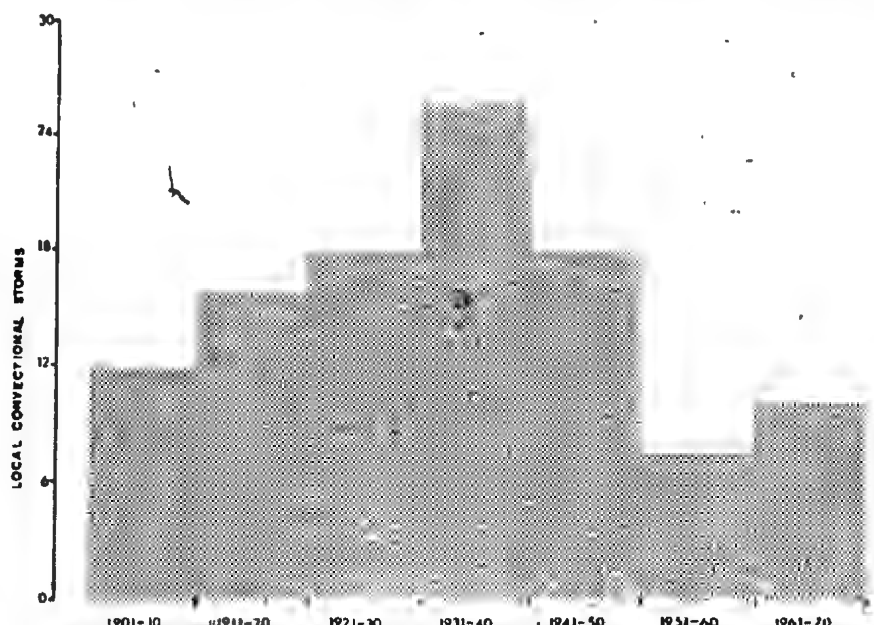


FIG. 26

DATA AFTER SKEETE
(1963 and 1973)

MEAN ANNUAL FREQUENCY (by decade) OF LOCAL CONVECTIONAL STORMS



DATA AFTER SKEETE
(1963 and 1973)

*This spans only half of a decade.

attained during the decade 1931-40 seems to have been experienced throughout the Caribbean; in fact, the period is often referred to as the "stormy 30's".[80]

After 1940, however, there was an appreciable decline, at least for the next two decades, in the frequency of these systems at Barbados. From the peak of 1931-40, the incidence decreased to thirteen in the 1941-50 period, to as low as five during the decade 1951-60. In the following decade the incidence of storms and depressions rose in excess of 50 per cent over that of the 1951-60 decade. Again, another decline appears to have set in since 1970; with half the present decade already gone only two storms have so far been recorded. In general, therefore, since 1901 there was a definite upward trend in the frequency of tropical storms and depressions lasting for a period of approximately 40 years, since which time there have been haphazard fluctuations.

There are little data from which the relative intensity of hurricanes, tropical storms and depressions which have affected Barbados can be accurately assessed. However, from the fragmentary records available there are indications that the synoptic systems which developed during the earlier part of the century might have been of greater intensity than those which affected the island later on. For instance, records compiled by Skeete[81] suggest that although far fewer hurricanes and storms were recorded prior to the late 1930's or early 1940's, they were, in general, associated with higher frequencies of flooding, stronger gales and higher

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80 The Climate of Jamaica, op. cit., p. 5

81 Skeete, 1963, op. cit., p. 28-36.

rainfall totals than those occurring later. In fact, the only real marked departure from this trend was hurricane "Janet" of 1955 when gusts in excess of 55 ms^{-1} were recorded; and even then there was little flooding, the maximum rainfall associated with that hurricane being only 63.5 mm. in the southern coastal districts.

The data also suggest that there has been somewhat of a *shift* in terms of the *timing* of these storms and hurricanes. For whereas these synoptic systems tended to develop most often in the earlier part of the hurricane season prior to 1940, they showed a tendency towards later occurrence after that date. For example, of all the tropical storms, depressions and hurricanes which were recorded between 1900 and 1940, approximately 65 per cent occurred during the months of June, July and August; the remaining portion occurred between the months of September and November. However, between the years 1941 and 1975, there was an almost complete reversal of the former situation. During this period about 63 per cent of all disturbances were recorded in the months September through November, while only 37 per cent occurred in the earlier part of the season.

D. Local Convectional (thunder) Storms

Local convectional storms have exhibited much the same pattern in their frequency of occurrence as tropical storms and depressions. There was an uninterrupted upward trend in the decadal frequency of these storms from 1901 which reached a peak in the years 1931-40. It may be recalled that this is the same decade during which the highest frequency of tropical storms was recorded. After this period there was a marked decline culminating in a minimum during the decade 1951-60. Between the years 1961-70, the incidence of these storms increased again, [illegible]d not exceed the number recorded during the decade 1901-10. (see figure 26).

It may be of interest to note that the trend in the incidence of tropical storms and local thunder storms shows generally good correspondence with the pressure graph in figure 13. It can be seen that the highest incidence of these storms occurred in the earlier decades of the century when mean atmospheric pressure was lowest. This is hardly surprising in the case of tropical storms; but this finding could open the way to new lines of investigation into the nature and physical processes behind the formation of local convectional storms. For it could be that reduced atmospheric pressure might also be a key factor in the initial development of these weather systems.

Since local convectional storms usually develop under conditions of low wind velocity[82], it was felt that there might be some correspondence between periods of generally low wind velocity and periods of high frequency of these storms. However, when figures 13 and 26 are compared, a rather unexpected relationship seems to occur. The diagrams indicate that the period of highest mean wind velocity coincides roughly with the period of highest incidence of local convectional storms. Hence this need not imply that wind velocity and convectional storm frequency are uncorrelated, since convection can be mechanically as well as thermally induced. At the same time, wind velocity is a highly variable parameter so that the mean annual values might not be representative of the conditions under which these

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[82] Skeete suggests that the development of these storms is unlikely where the wind velocity exceeds approximately 4 ms^{-1}.

storms have developed. Since these are strictly daytime phenomena and their initial development starts soon after sunrise, wind velocity readings at approximately 7 a m. or 8 a.m. would be more meaningful. At the same time, the values for wind speed which have been employed in the analysis have been calculated from data recorded at Seawell and Codrington Stations. In the absence of other data, these have been assumed as representative of conditions everywhere on the island. This need not be an entirely reliable assumption, especially considering the possible effects of such local controls as topography, altitude and exposure.

Perhaps sunshine duration hours might have proven a more reliable index against which to measure the fluctuations in frequency of local thunderstorms. It has already been established that this is an important parameter in the genesis of these systems. But unfortunately, there are no data on hours of sunshine duration prior to 1937, thus it is difficult to make reliable pronouncements on any relationship which might exist between the two parameters.

E. Rainfall and Synoptic Weather Systems

Although a large percentage of the island's rainfall is said to be associated with the passage of tropical storms and hurricanes, no significant statistical relationship can be found between these variables. Correlation coefficients were calculated between island mean rainfall totals by decade and the decadal frequency of tropical storms and hurricanes. The low coefficient, $r = +0.07$ (for hurricanes and rainfall) was only significant at the 20% level. To further measure the statistical association between the parameters correlation was also attempted between the decadal rainfall amounts for the seven sample stations and tropical storm and hurricane activity. Some of the resulting coefficients were slightly better but nevertheless, statistically insignificant; none were significant beyond the 15% confidence level.

However, since the passage of tropical storms and hurricanes coincides with the island's *normal* wet season, correlation coefficients were computed between the decadal frequency of these disturbances and island *wet season rainfall*, by decade. In this particular instance, *wet season rainfall* was computed as the sum total recorded between the months of June to November inclusive. There was no significant correlation found between hurricane frequency and island mean rainfall during the wet season; but there was a weak, positive relationship between the frequency of tropical storms and *wet season rainfall*. The coefficient $r = +0.18$ was significant at the 10% level, compared to $r = +0.08$ in the case of hurricanes which barely reached the 20% level of significance.

It is not surprising that rainfall during the wet season shows better correlation with tropical storms and depressions than with hurricanes. For one thing, hurricanes occur far less frequently in the Caribbean than storms and depressions. In fact, it has not been uncommon in the past for the island to be unaffected by passing hurricanes for periods as long as 5-8 years in succession. But so much more frequent is the development of depressions and storms during a *normal* season, that they have been found to occur in the Caribbean as a whole with a statistically predictable frequency of one every four or five days.[83]

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[83] Riehl, op. cit. p. 325

No correlation was attempted between the frequency of local convectional storms and mean island rainfall, inasmuch as these systems are highly localised phenomena and their effects normally confined to specific localities on the island. However, the frequency of these systems and rainfall totals from the three stations (Holetown, District 'E' and Lion Castle) which normally fall within their sphere of influence were correlated. Again, insignificant statistical correlation coefficients of $r = +0.10$, $r = +0.07$, $r = +0.12$ for Holetown, District 'E' and Lion Castle, respectively, resulted.

With the possible exception of hurricanes, therefore, no clear cyclical rhythm has emerged from the analysis of the frequency of these synoptic systems. In the case of hurricanes there is some evidence which appears to suggest that years of decreasing and increasing frequency tend to alternate at rough intervals of three decades. Where tropical storms, depressions and local thunderstorms are concerned, only very broad trends are evident; and furthermore, these trends are only clearly discernible prior to 1940. Since this period no clear trend or rhythm has emerged as these systems tended to fluctuate rather haphazardly in their frequency of occurrence.

Chapter 6

Summary

In the foregoing chapters an attempt was made at analysing the major fluctuations and long-term trends in the climatic data of Barbados post 1900. Generally, it was found that the variations observed in the island's recent climatic history have been in keeping with postulated patterns of hemispheric change and more especially, with the rate of change observed in other low-latitude regions. That there have been significant identifiable periods of fluctuation in the island's past climate can be in no doubt; it is only the physical causes and full implications of these variations which are not fully understood. Some of the major findings of the study are briefly summarised below.

A warming trend was observed between the years 1903 and 1949, altogether corresponding to a net temperature increase of approximately 1°C. It was also shown that a similar trend was observed at other locations in the region, for example, in Jamaica to the northwest and Trinidad to the southeast. Furthermore, the rate of increase in temperature in Barbados during this period agrees to a large extent with a previous finding by Callendar.[84] He notes an increase of nearly 1°C from the late 1800's up to the 1940's for most areas in the tropics, including India, Africa, the West Pacific and South America. Since the late 1940's or early 1950's however, there has been an apparent reversal of this trend; despite minor upward fluctuations there has been an overall net decrease of approximately 0.2°-0.3°C between 1949 and 1975. Again, the latter downward trend appears to be in rough phase with a similar trend identified for several

[84] Callendar, *op. cit.*, pp. 1-12.

areas in the Northern Hemisphere. The works of Longley[85] and Lamb and Johnson[86] are noteworthy in this respect.

However, it has already been pointed out that there is some controversy over the recently postulated *cooling* trend; whether or not this tendency is global in extent is not yet clear. In some parts of the Northern Hemisphere temperatures appear to be still rising, while in other areas, such as Australia and the Black Sea region, there have been no noticeable fluctuations since the 1940's. In fact, temperatures seem to have remained quite stable in these areas from the 1940's up to the present. In 1969 Davitaya[87] warned that this apparent cooling tendency might simply be a fluctuation temporarily interrupting the warming trend. Furthermore, quite recently at least one study seems to have confirmed Davitaya's suspicions. In 1975, Angell and Korshover[88], in an analysis of mean tropospheric temperatures since 1958, found no evidence of cooling but rather suggested that *global* temperatures had either stabilised or were showing a slight tendency to increase.

It was also discovered that prior to 1940 pressure and wind fluctuations in Barbados were generally out of phase. This was a rather unexpected occurrence since it was earlier demonstrated that there is a positive relationship between the annual variation of mean atmospheric pressure

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[85] Longley, op. cit. pp. 207-211.

[86] Lamb and Johnson, op. cit. pp. 94-133.

[87] Davitaya, op. cit. p. 552.

[88] Angell, J.K. and Korshover, J., "Estimate of the Global Change in Tropospheric Temperature Between 1958 and 1973", Monthly Weather Review, Vol. 103, 1975, pp. 1007-1012.

and the annual variation in mean wind speed. However, after 1940 fluctuations of both parameters tended to parallel eath other. For instance, there was a noticeable decrease in both pressure and wind velocity between 1940 and the early to mid 1960's, although pressure decreased more rapidly than wind speeds. Thereafter, a slight upward trend was observed but again, pressure appeared to increase at a rate slightly in excess of wind velocity.

There has been a rough quasi-cyclic pattern in the island's past rainfall regime, with fairly prolonged periods of low rainfall alternating with periods of increased precipitation. It has also been demonstrated that although there is evidence of some slight spatial variation (in terms of the onset and ending of fluctuations) the general pattern of rainfall has been remarkably similar at all locations. Altogether there were approximately seven distinct fluctuation periods but of these the major ones were 1920-30, the late 1940's and early 1950's - mid 1960's and 1966-75. The years 1920-30 stand out not only because this was the driest period in the island's rainfall regime post 1900, but also because fragmentary historical records suggest it to be perhaps the driest phase in the island's known climatic history. The years commencing from the early 1950's right up until about 1965 easily constituted the wettest period since 1900. During this maximum, the rainfall at all stations was at least 20 per cent in excess of the mean value recorded during the 1920-30 minimum. What makes the post 1965 period appear significant is the fact that this signalled the start of a noticeable decrease in rainfall at all locations. It is remarkable that with the possible exception of the earlier minimum, this is the only period when rainfall fluctuations have been in exact phase (in terms of *timing*) at all stations. It appears too that mean annual rainfall is decreasing at a relatively rapid rate at most locations, a rate which closely approximates that which was observed during the 1920-30 period. What is more, the post 1960 period has been shown to be one of rapidly decreasing rainfall at most tropical locations, and this trend has been predicted to continue for at least another two decades or so.[89]

Although so far no strong statistical relationship can be said to exist in the overall pattern between the frequency of tropical storms and hurricanes and rainfall in Barbados, two important observations can nevertheless be made. In the first place, it was discovered that the period of lowest rainfall corresponded almost exactly with the decade of least hurricane activity. During the decade 1921-30 only three systems of hurricane intensity passed close enough to the island to affect weather conditions, the lowest number recorded in any decade since 1900. At the same time, the rainfall maximum of the 1950's to mid 1960's was found to be associated with the period of greatest hurricane activity; for during the decade 1951-60 a record thirteen hurricanes affected the island's weather. Although it might be a little premature to imply a causal relationship, it seems more than just a "matter of chance" that these major fluctuations should coincide. Similarly, it is small wonder that wet season rainfall, that is the total recorded between the months of June - November, shows a weak positive relationship with hurricane frequency.[90]

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[89]Willett, H.C., Do Recent Climatic Trends Portend an Imminent Ice Age? in Kopec, R.J. (ed.) Atmospheric Quality and Climatic Change. Univ. of North Carolina, Dept. of Geog., Studies in Geography No. 9, 1976, p. 32.

[90]It should be borne in mind that the wet season and the hurricane season approximately coincide.

It is worth noting that most of the major variations of climate identified for Barbados during the period 1900-75 have been associated with major flucutations of the hemispheric circulation patterns. For instance, Dzerdzeevskii[91] found the temperature increase of earlier decades to be associated with increased zonal circulation whereas he found the recent *cooling* to be closely connected with more meridional flow. This was later substantiated by the work of Kalnicky[92] who demonstrated that the general atmospheric circulation over the Northern Hemisphere was distinctly zonal between 1900 and 1950 but showed a tendency towards increased meridionality ever since then. Similarly, the observed changes in hurricane frequency prior to and after 1950 show rough correspondence with these circulation changes. The rainfall decreases in mid latitude and tropical regions since the 1960's have been attributed to a weakening of both the zonal Westerlies and the North Atlantic Trades by Lamb.[93] More recently, Winstanley[94] pointed out that the decrease in tropical rainfall in recent years was a result of a contraction of the tropical meridional circulation. It is noteworthy that the marked reduction in Barbados rainfall since the mid 1960's seems to be in some way related to these latter circulation changes. This again seems to lend support to the present contention that the best explanation of precipitation fluctuations appears to to lie in a more thorough understanding of variations in the general circulation of the atmosphere.

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[91]Dzerdzeevskii, op. cit., pp. 285-292.

[92]Kalnicky, op. cit., pp. 100-112.

[93]Lamb, 1966, op. cit., p. 210.

[94]Winstanley, op. cit., p. 190.

This study then might be regarded as a new line of enquiry into the recent climatic past of the island of Barbados. It has attempted to identify and analyse the nature of climatic fluctuations since 1900; and has assessed the approximate rates and directions of such changes in relation to other postulated hemispheric and latitudinal climatic fluctuations. The results, therefore, may be used as an initial base for further research, especially with a view to long-range forecasting and planning. Some of the findings, for example, could have far-reaching implications for local agriculture. The economy of Barbados is still primarily agricultural, with almost total dependence on the production of sugar cane. It is undeniable fact that rainfall is the single most important environmental factor affecting sugar cane growth; and it has further been demonstrated that fluctuations in rainfall are usually reflected by fluctuations in sugar cane yields.[95] Hence, it is felt that an understanding of past rainfall fluctuations and trends, for instance, could prove useful in the future as an aid to long-term agricultural planning and water resource management.

Yet, great caution must be exercised if the results of studies such as this are to be used as tools for predicting future climatic events. At the present state of knowledge, the real physical basis of climatic change is little understood. For if could be misleading to assume that climate will behave in the future as it has in the past; and this is the main premise from which present-day long-term predictions are given. For until

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[95] Rouse, op. cit., p. 75. See also Hudson, J.C., Fire, Water and Sugar Produbtion in Barbados, - Paper Published by the Barbados Sugar Producers' Assoc., 1973, pp. 1-7.

a more thorough understanding of the real physical causes of climatic change is achieved, any predictions based solely on past events must continue to be regarded as highly speculative.

APPENDIX I

Table 12

Mean Annual Atmospheric Pressure for Codrington and Seawell,

1942 - 60 (mbs.)

Year	Codrington	Seawell
1942	1013.5	1013.5
1943	1013.5	1012.8
1944	1013.7	1013.0
1945	1013.0	1013.9
1946	1012.7	1012.2
1947	1013.0	1012.3
1948	1013.7	1013.8
1949	1011.8	1012.0
1950	1011.7	1012.1
1951	1013.9	1014.0
1952	1013.7	1013.7
1953	1012.2	1011.9
1954	1011.8	1012.0
1955	1012.2	1012.2
1956	1012.4	1012.4
1957	1013.2	1013.1
1958	1013.1	1013.0
1959	1013.3	1013.2
1960	1013.9	1013.9

Table 13

Mean Annual Temperatures for Codrington and Seawell,

1942 - 60 (^{o}C)

Year	Codrington	Seawell
1942	26.5	26.6
1943	26.1	26.1
1944	26.1	26.3
1945	26.4	26.6
1946	26.7	26.8
1947	27.1	27.1
1948	26.8	26.8
1949	26.6	26.7
1950	26.4	26.4
1951	26.6	26.8
1952	26.8	26.9
1953	26.7	26.7
1954	26.0	26.0
1955	26.0	26.0
1956	25.9	25.9
1957	25.8	25.9
1958	26.3	26.4
1959	26.0	26.2
1960	26.1	26.2

Table 14

Mean Annual Relative Humidity for Codrington and Seawell,

1942 - 60 (%)

Year	Codrington	Seawell
1942	73	73
1943	72	74
1944	74	73
1945	73	74
1946	75	73
1947	70	68
1948	66	67
1949	67	68
1950	68	70
1951	70	69
1952	75	75
1953	74	73
1954	73	72
1955	73	74
1956	74	75
1957	74	75
1958	75	74
1959	76	76
1960	77	74

Table 15

Mean Annual Sunshine Hours for Codrington and Seawell, 1942 - 60

Year	Codrington	Seawell
1942	8.0	8.1
1943	8.2	8.4
1944	8.2	8.3
1945	8.5	8.5
1946	8.5	8.6
1947	9.0	9.1
1948	8.5	8.5
1949	8.5	8.6
1950	8.0	8.1
1951	8.1	8.1
1952	8.7	8.8
1953	8.0	8.2
1954	8.3	8.4
1955	8.3	8.3
1956	8.3	8.3
1957	8.3	8.3
1958	8.6	8.7
1959	8.8	8.9
1960	8.7	8.7

APPENDIX II

FIG 27(a)

DISTRICT E RAINFALL FLUCTUATIONS

Monthly Totals

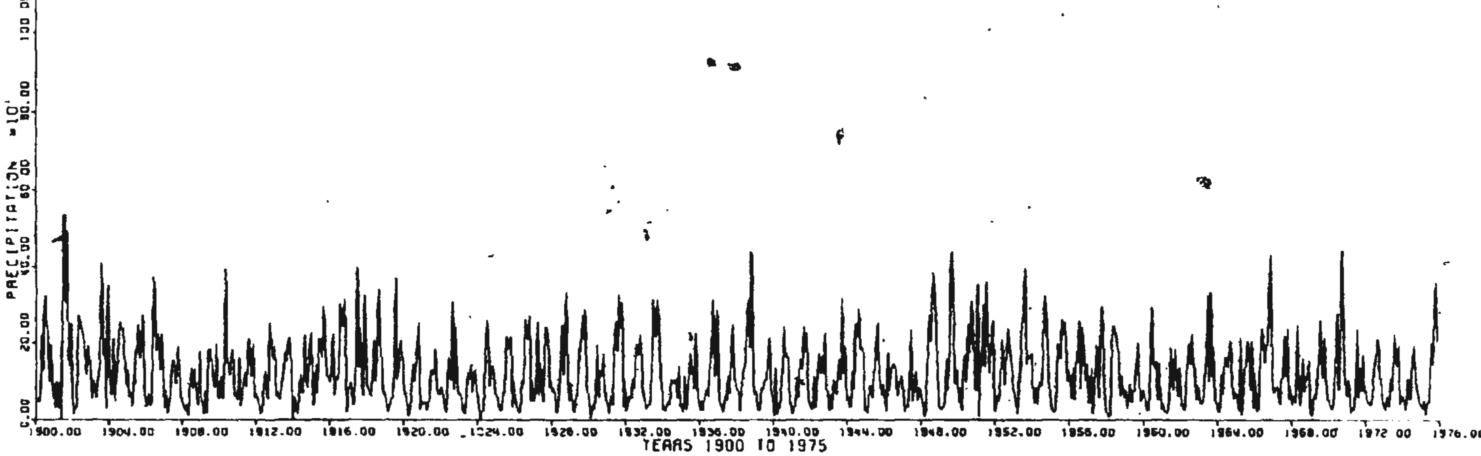
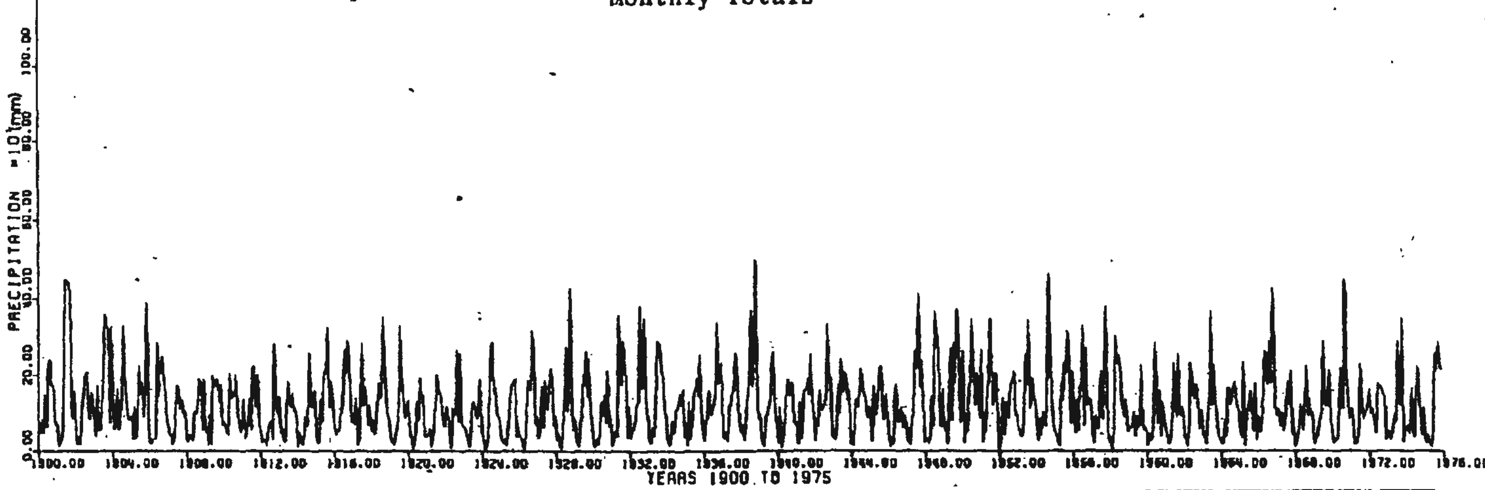


FIG 27(b)

HOLETOWN RAINFALL FLUCTUATIONS

Monthly Totals



DATA SOURCE: CARIBBEAN METEOROLOGICAL INSTITUTE

FIG 27(c)

SEARLES RAINFALL FLUCTUATIONS

Monthly Totals

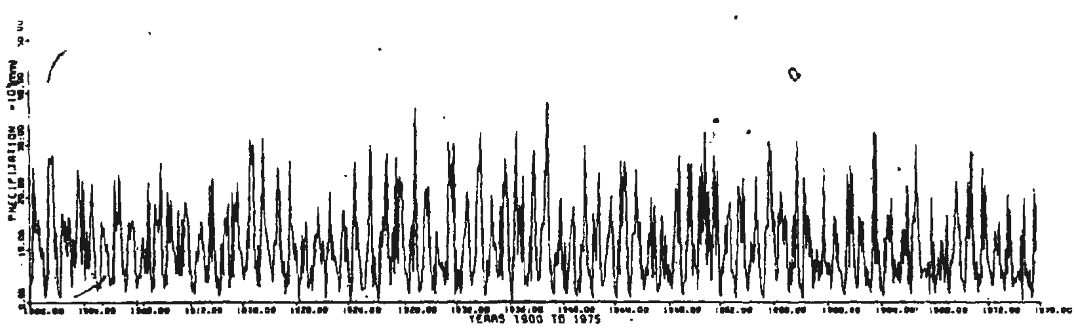


FIG 27(d)

DISTRICT 'C' RAINFALL FLUCTUATIONS

Monthly Totals

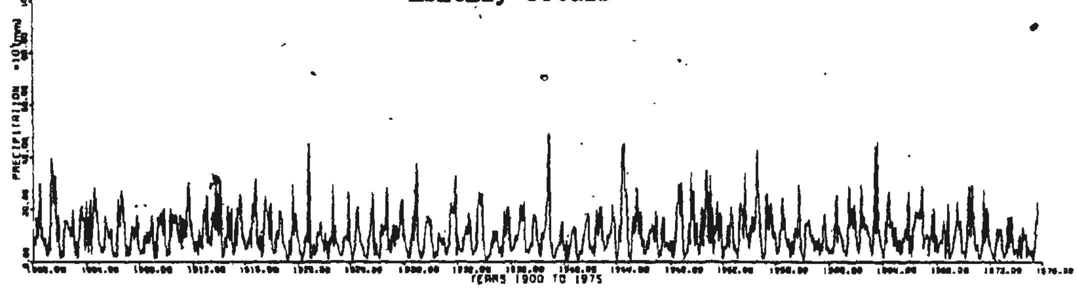


FIG 27(e)

CENTRAL RAINFALL FLUCTUATIONS

Monthly Totals

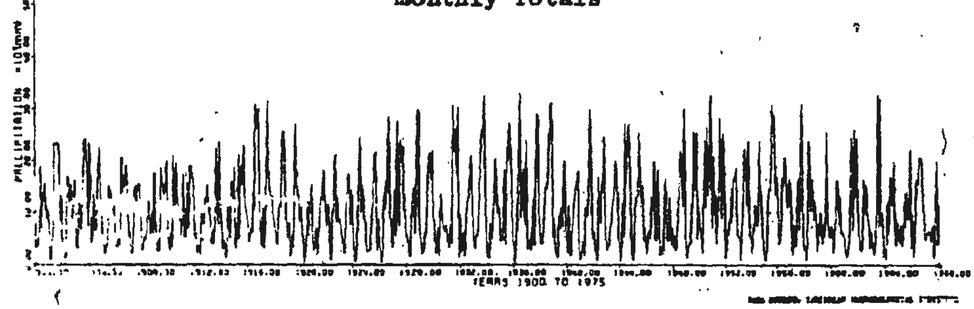


FIG 27(f) **LION CASTLE RAINFALL FLUCTUATIONS**

Monthly Totals

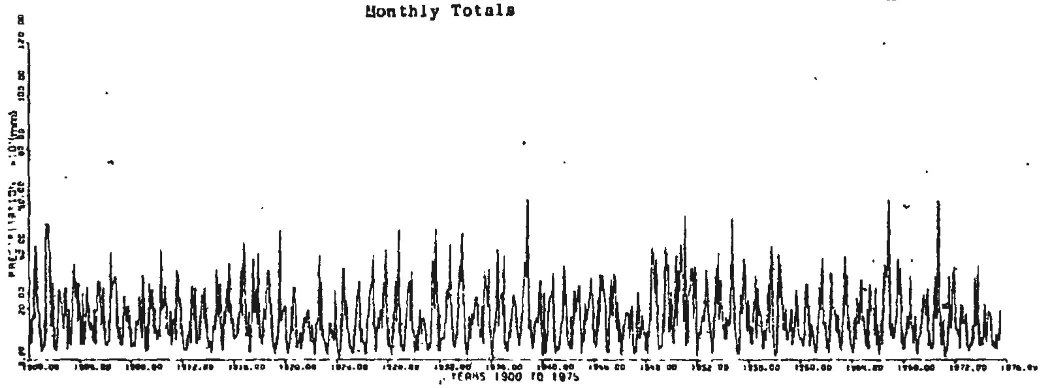
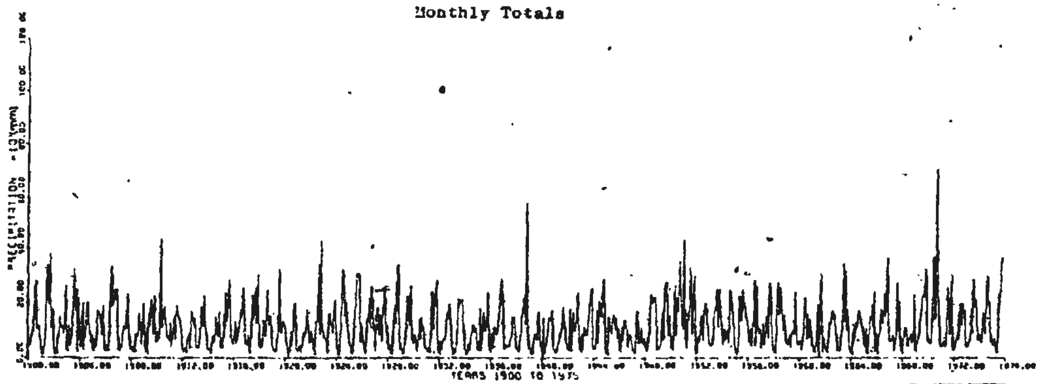


FIG 27(g) **DISTRICT F RAINFALL FLUCTUATIONS**

Monthly Totals



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FRONTISPIECE

BARBADOS-TOPOGRAPHIC MAP
contours in metres