

THE CLIMATE OF BARBADOS

by

Samuel Edwin Tandoh

A thesis submitted to the Faculty of
Graduate Studies and Research in partial
fulfilment of the requirements for the
Degree of Master of Science.

Department of Meteorology
McGill University
Montreal

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PREFACE

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I should like to express my gratitude to Professor T. Hills, Mr. W.R. Rouse and Mr. David Taut, of the Department of Geography, McGill University, for providing me with data on Barbados. My thanks also go to my typist, Mrs. Goff, for her patience and help.

Finally, I wish to pay a tribute to my wife, Faustina, for her continued support and unfailing encouragement.

CHAPTER I

INTRODUCTION

Aim of Thesis

The McGill University Tropical Research Station was set up in 1958 at Waterford, Barbados, under the Department of Geography for the purpose of

(a) making meteorological and climatological measurements at a tropical station.

(b) establishing a case for Agricultural Meteorology in a region densely populated and dependent largely on Agriculture.

(c) creating a Graduate Centre for investigations and research into aspects of Tropical and Caribbean Geography.

The aim of this thesis is

(a) to analyse five years of published climatological data in order to obtain detailed climatological statistics for reasearch workers, and also to serve as a basis for describing the climate of Barbados.

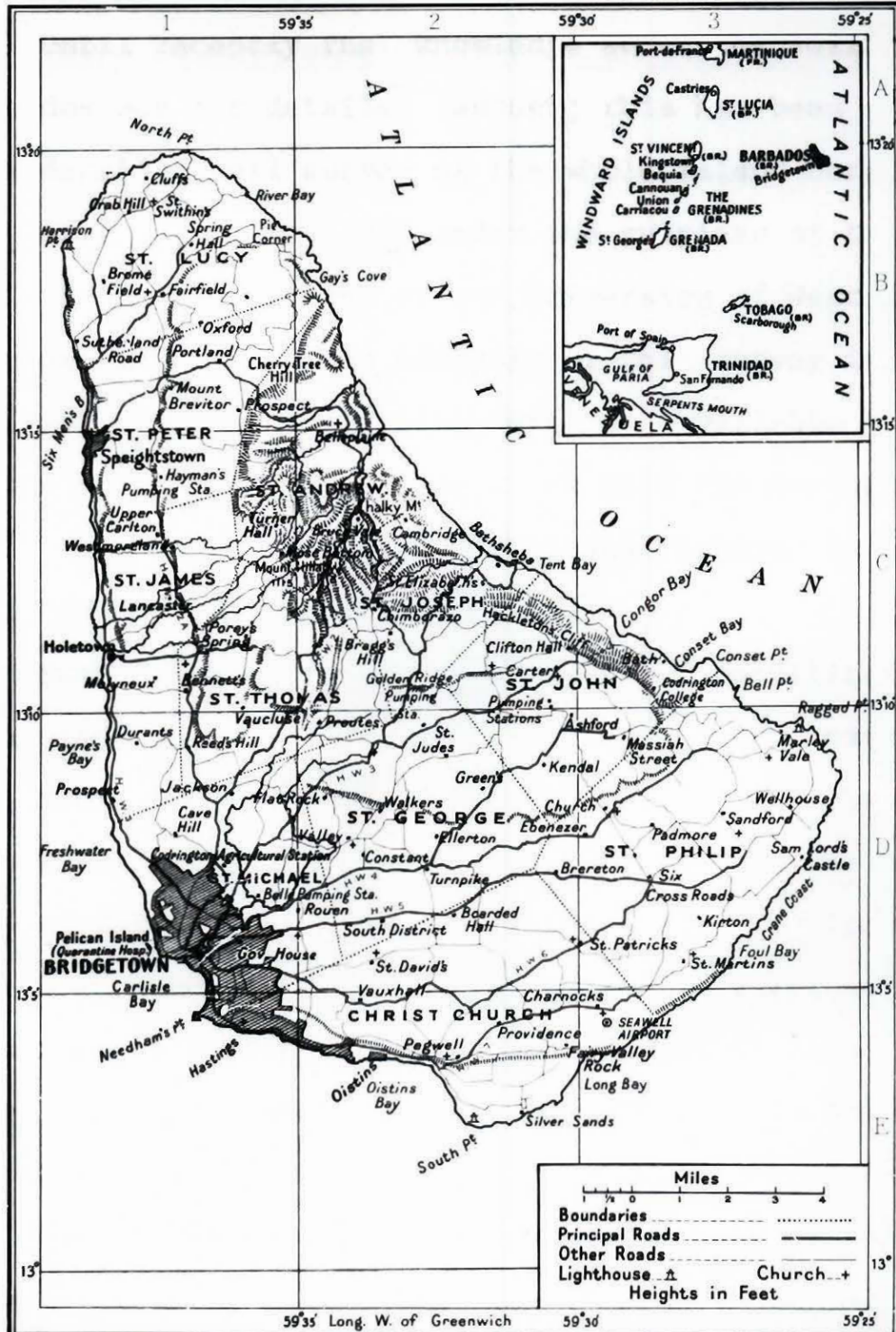
This is the main part of the thesis.

(b) to give explanatory causes of the variations in climate, both seasonal and aperiodic, especially of temperature and rainfall regimes, at Waterford in particular, and the whole island in general.

Position and Topography of Barbados

Barbados is the easternmost of the Leeward Islands of the West Indies. It is positioned at Lat. 13° 10'N and Long. 59° 35'W. (Fig. 1) It lies

BARBADOS 5



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Compiled and drawn by Directorate of Colonial Surveys.
Photographed by D.C.S. and printed by G.S.G.S. 1956.

well within the Tropics, and has the same northern latitude as Niamey (West Africa), Madras (India), and Manila (Philippines). It is 21 miles long and 14 miles wide, having a total area of 166 square miles.

Physically, the Island is flat to the south and west and rises towards the northeast to the highest point in the Island, Mt. Hillaby, which has an altitude of 1,115 feet, (Fig. 2). From the west the rise takes the form of a series of well-defined limestone terraces, while to the north, east and south, the steplike rises are less obvious. Along the east coast, i.e. the coasts of St. Joseph, St. John, and St. Andrew, the highly distorted folds of the Scotland formation rise sharply from the sea and in places create a definite cliff.

The Island is covered mainly by the red, black and undifferentiated Scotland soil. Red soils are associated with high rainfall upland areas, while black soil is associated with low rainfall lowland areas.

(Rouse 1962)

Position and Topography of Waterford Station

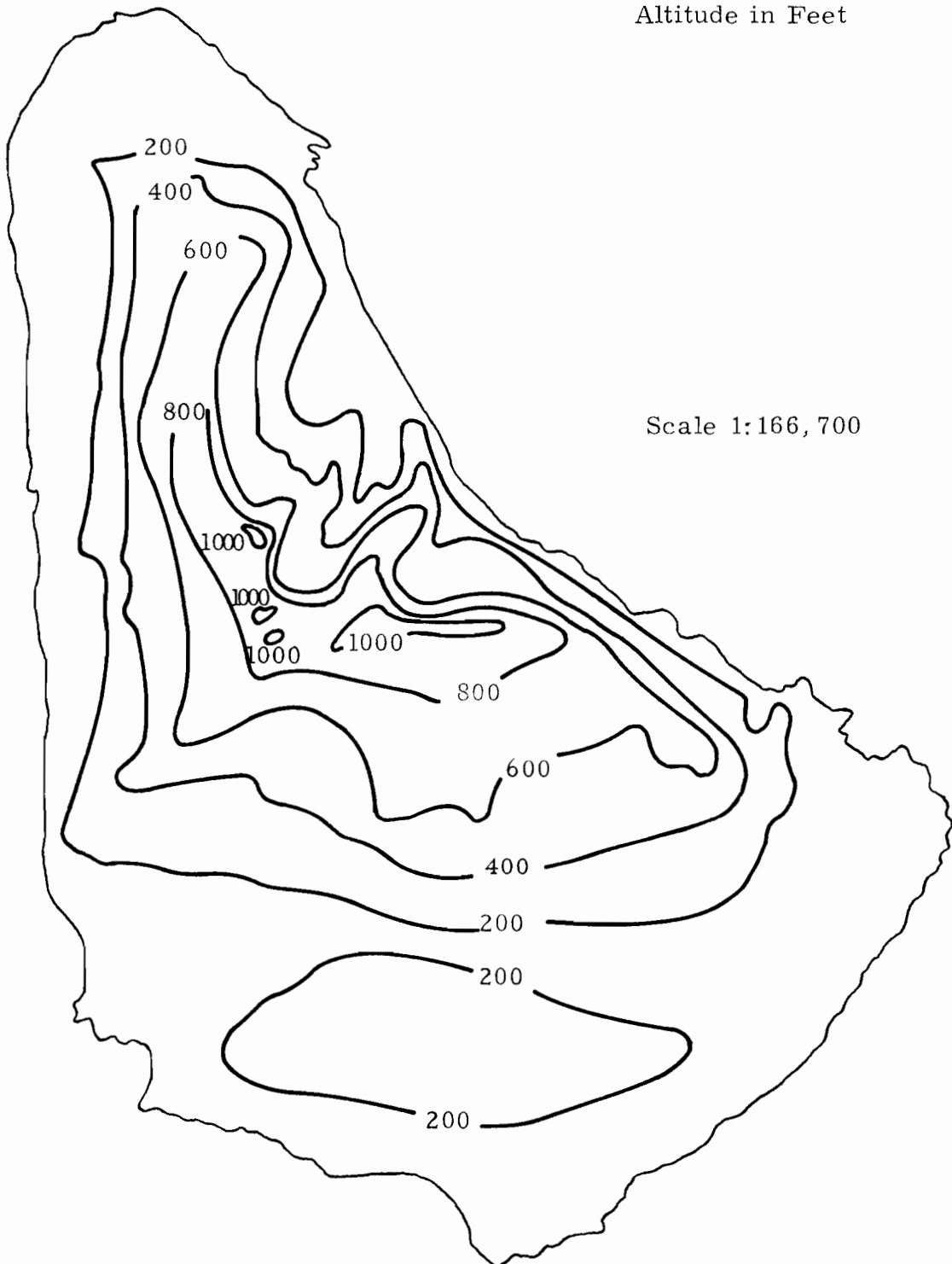
"The Station is situated two miles north east of the city, Bridgetown, at a point where the East-West St. George valley syncline, running across the south centre of the island, separates the Christ Church ridge of the south from the main hills and terraces of the north (Fig. 3). It lies to the western end of the syncline, where the latter opens out again towards the west coast. It is approximately 120 feet above sea level, and flanked on

FIG. 2

TOPOGRAPHIC MAP
BARBADOS

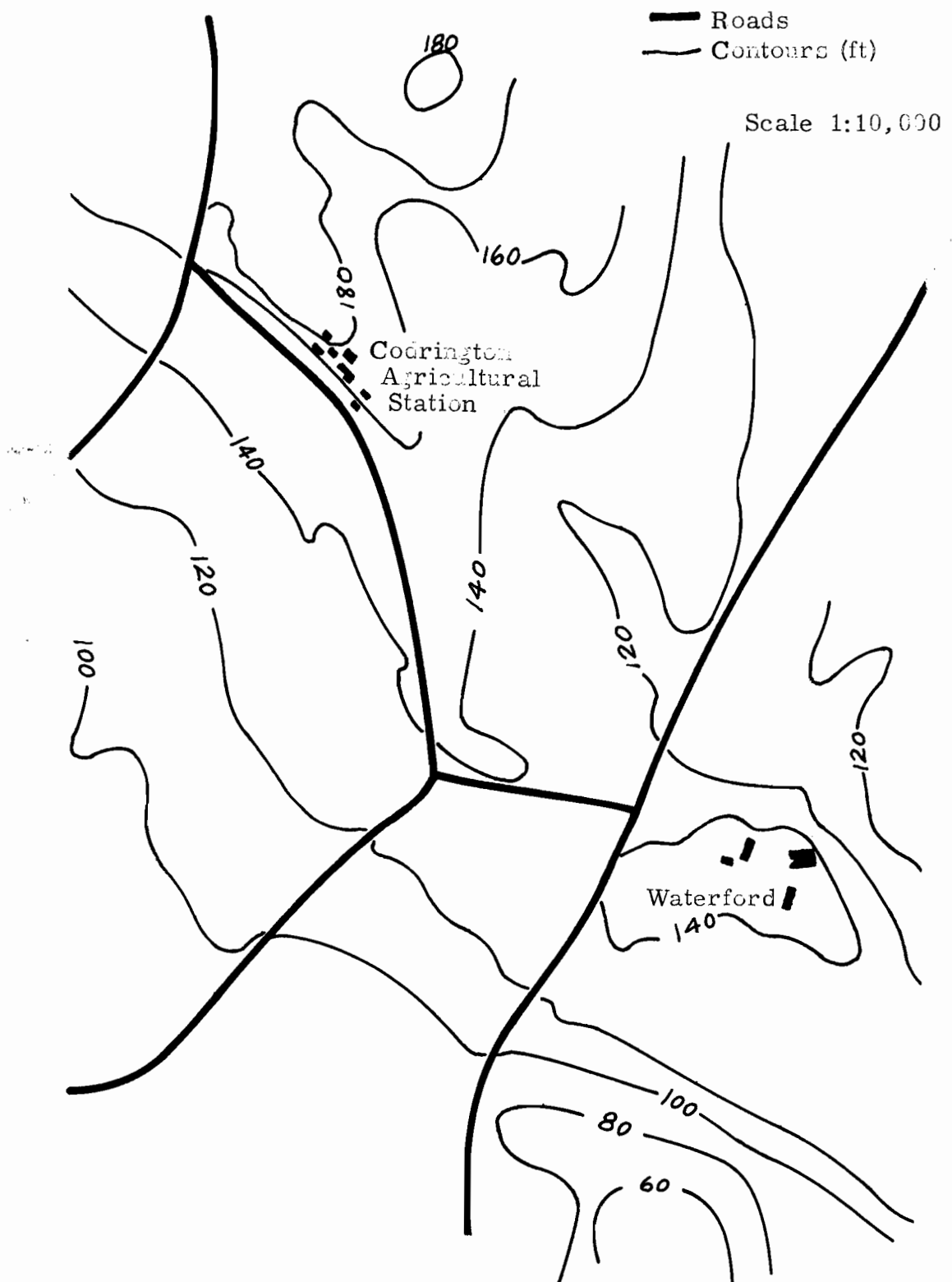
Altitude in Feet

Scale 1:166,700



(After W.R. Rouse)

FIG. 3 POSITION AND TOPOGRAPHY OF
WATERFORD STATION



the north west at approximately a half mile away by a gently sloping spur on which the Headquarters of the Agricultural Station are located. This spur slopes towards the south east. The McGill Station lies south centre of the syncline below the level of the Codrington Station which is situated on the moderately broad top of the spur at about 190 feet above sea level.

Codrington Station is also the site of the Government Meteorological Station which has been in operation since the last quarter of the 19th century, and which is administered through the Department of Science and Agriculture. Meteorological records have been collected for this station over a number of years.

Only one other Meteorological Station exists on the island. This is the Seawell Airport Station situated on the south east coast of the island, and administered under the Federal Meteorological Service. This station was set up in the fourties when air traffic was beginning to increase in the islands." (McGill University, 1959)

Data Series

The data series used for analysis consist of surface observations of weather elements at Waterford Station over a period of 5 years, from March 1959 to February 1964. Publication of data started in March 1959 and has been continuing up to now. The data are published every four

months in "Climatic Observations at Waterford, Barbados, West Indies, Tropical Research Laboratory" by the Department of Geography, McGill University. Both the individual daily values and the monthly means are published. Most of the important climatological elements are observed. All observations are instrumental. Much of bias and subjectivism that are inherent in direct human observation are perhaps almost absent. However, human or visual observation of weather phenomena such as visibility, cloudiness, occasions of thunderstorms, etc., are important climatologically. These were, unfortunately, not published.

Errors can exist even in instrumental observations. These may be accidental errors such as reading the instrument wrongly, or having made the correct reading, to record it wrongly. Sometimes there is the error due to the instrument itself. Some of these errors can be eliminated by subjecting the records to careful scrutiny and rejecting all doubtful figures before publishing the data. This has been done in the case of the data series used.

A knowledge of the type of instruments used is essential to enable one to have an idea of the accuracy of the data and also to be able to know the possible sources of error and their magnitude. Moreover, when the instruments are of the standard meteorological type they make the data comparable with data in other places using the same type of instruments. This is essential in regional climatology. The type of instruments used are therefore given in Appendix 1.

Exposure of instruments and method of observation also affect the accuracy of the data. Exposure affects not only the comparableness of the observations, but also affects considerably the value of the element measured. By means of the right exposure local influences are avoided, thus making the data comparable spatially.

Different instruments need different exposures. For example, in the measurement of air temperature the exposure must be such as to avoid local influences of solar radiation and thermal stratification. In case of wind speed, nearness of obstacles and height at which observations are taken affect the measurements; the place of measurement must therefore be open without any obstructions nearby. The height at which observations are taken must be known and, better still, standardized. In the case of rainfall the wind speed and the resistance offered by the air to the water drops affect the amount collected. The height of the rim and surface area of the gauge must therefore be known, and water splashing into the gauge must be avoided at all costs. "The ordinary rule for installing a gauge is that it should not be closer to an obstruction than the height of the obstruction. This is much too close if a better exposure can be obtained. Three times the height of the obstruction should be a safe distance, even if the object is a solitary tree." (Middleton and Spilhaus 1953). Exposure of the instruments used at Waterford Station is described in Appendix 1.

All changes in meteorological instruments, be it method of observation, type of instrument, even if it is an improvement, or exposure, etc., break the continuity of the records and render them inhomogeneous. For example, the change of an ordinary thermometer to sling thermometer, although it constitutes an improvement in the observations, will render the records inhomogeneous by giving higher temperatures during the night and lower temperatures during the afternoon. (Conrad and Pollak 1962). All changes with respect to each instrument of the elements analysed are given in Appendix 1.

CHAPTER II

PHYSICAL CLIMATOLOGY

I TEMPERATURE

Daily Mean Temperature*

The annual average of daily mean temperature is 78.7° F.

The seasonal variation of daily mean temperature shows two maxima in JUNE and AUGUST. The higher peak occurs in JUNE with average daily mean temperature of 80.9° F, the difference in the two peaks being only 0.5° F. The coolest month is FEBRUARY with average daily mean temperatures of 76.2° F. The average annual range of temperature* is small, being only 4.7° F. DECEMBER through MARCH have lower temperatures, while APRIL through NOVEMBER have higher temperatures. Figures for daily mean temperature and a graph for its seasonal variation are given in Table 1 and Fig. 4 respectively.

Daily Maximum Temperature

The annual average of daily maximum temperature is 85.9° F. Its seasonal variation has the same pattern as that for the daily mean temperatures, except that the higher peak (87.3° F) occurs in AUGUST and the lower peak (87.1° F) in JUNE. MAY has a mean maximum temperature of 87.0° F, so that, in view of the shortness of the data series, the lower peak can probably occur in MAY also. The average annual range of maximum temperature is 3.5° F. There is therefore less seasonal variation in maximum temperature than in daily mean temperature.

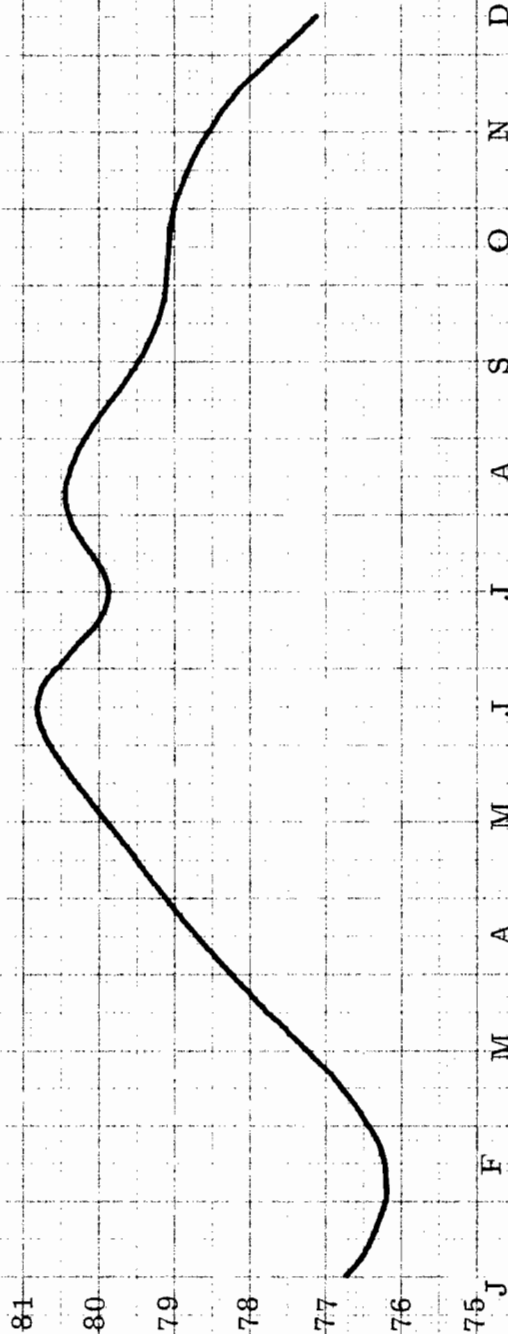
* Refer to Appendix 2

TABLE 1 MONTHLY MEAN DAILY MEAN TEMPERATURE (°F) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			77.1	79.0	78.5	81.5	79.5	81.0	80.0	79.1	78.5	78.2	78.8
1960	76.4	75.6	77.1	78.8	79.9	80.6	80.3	80.2	79.5	79.9	78.7	76.8	78.6
1961	77.0	76.5	77.0	78.4	80.8	80.9	79.6	80.8	79.4	78.8	78.8	76.6	78.7
1962	76.4	76.1	76.2	78.6	80.0	80.6	80.4	79.8	79.1	78.6	78.0	77.2	78.4
1963	76.4	76.5	78.0	78.5	79.6	80.8	79.8	80.3	79.6	79.2	78.8	77.2	78.7
1964	76.3	76.1											
AVR.	76.5	76.2	77.1	78.7	79.8	80.9	79.9	80.4	79.5	79.1	78.6	77.2	78.7

FIG. 4 DAILY MEAN TEMPERATURE (°F) WATERFORD BARBADOS

(March 1959 - February 1964)



The absolute maximum temperature* for each month is not very different from the mean maximum temperature, the difference between the two not exceeding 4.0° F for any month. It may be inferred that cases of extreme maximum temperatures are likely to be rare. In fact, the highest maximum temperature on record for the 5 year period is 91° F, registered on the 25th of August 1959. Figures for monthly mean daily maximum temperature and absolute maximum temperature are given in Tables 2 and 3. Graphs, showing their seasonal variation, are also depicted in Fig.5.

Daily Minimum Temperature

The annual average of daily minimum temperature is 71.4° F. Its seasonal variation, unlike the maximum temperature, shows only one peak which occurs in JUNE (74.6° F). The lowest minimum temperature (67.7° F) occurs in FEBRUARY. The average annual range of daily minimum temperature is 6.9° F. Minimum temperatures thus show greater seasonal variation than either the daily mean temperature (4.7° F) or the daily maximum temperature (3.5° F). Unlike absolute maximum temperatures, absolute minimum temperatures differ significantly from the mean minimum temperatures, the difference between the two from month to month ranging from 4.6° F to 10.0° F. Cases of extreme minimum temperatures are therefore likely to occur. The lowest minimum temperature on record during the 5 year period is 59.4° F, registered

* Refer to Appendix 2.

TABLE 2 MONTHLY MEAN DAILY MAXIMUM TEMPERATURE OF WATERFORD
(°F)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			85.0	86.0	86.0	88.0	87.0	89.0	88.0	86.0	85.4	85.7	
1960	84.6	84.8	85.3	85.9	87.1	87.0	86.3	86.4	87.1	86.3	86.7	84.6	86.0
1961	84.5	84.6	85.5	86.7	87.3	87.4	85.5	86.9	86.4	85.1	85.7	83.7	85.8
1962	82.6	83.0	84.8	86.8	87.9	86.7	86.5	86.6	85.5	85.8	85.6	84.2	85.5
1963	83.9	85.1	85.1	87.1	86.7	86.5	85.4	87.4	86.8	86.7	85.8	84.3	85.9
1964	83.5	84.8											
AVR.	83.8	84.5	85.1	86.5	87.0	87.1	86.1	87.3	86.8	86.0	85.8	84.5	85.9

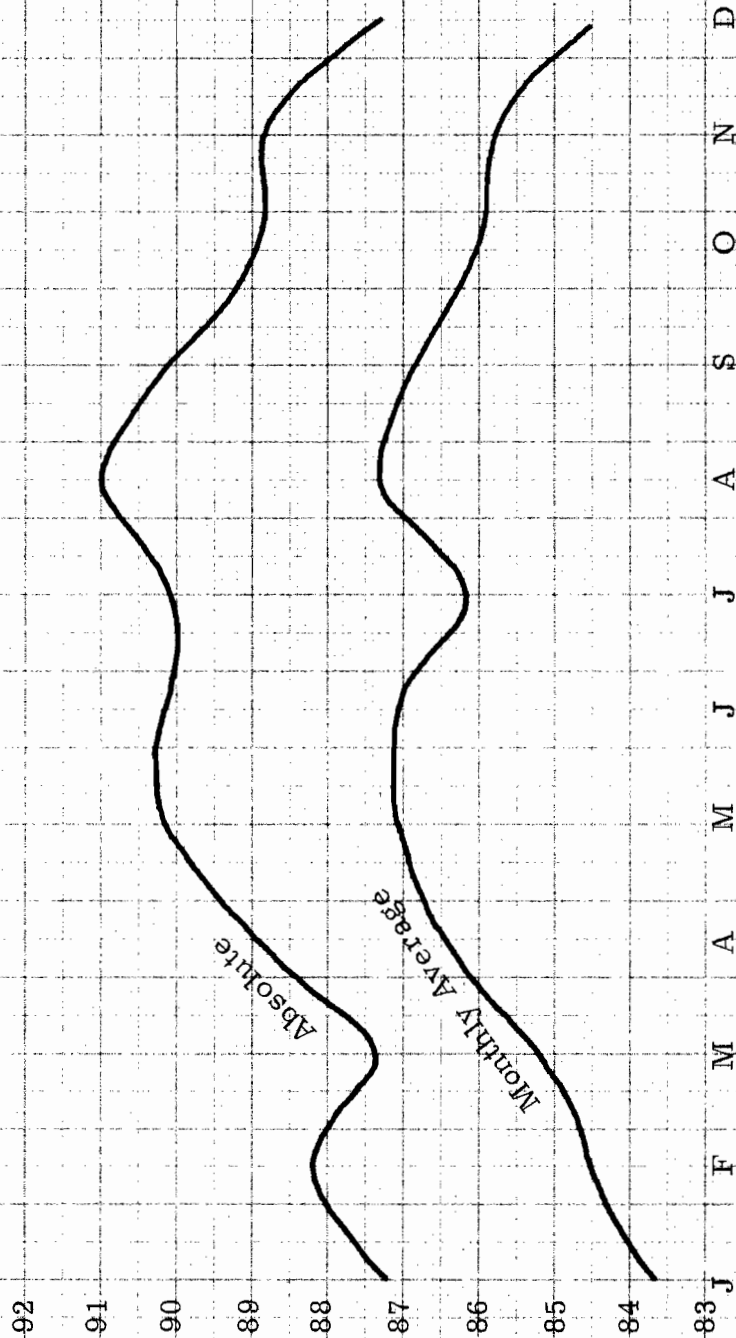
TABLE 3

ABSOLUTE MAXIMUM TEMPERATURE OF WATERFORD
(°F)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			87.0	89.0	88.0	89.0	90.0	91.0	90.1	88.9	87.5	87.1	91.0
1960	86.7	86.3	87.1	87.7	88.7	88.8	87.8	87.9	88.9	88.5	88.2	86.2	88.9
1961	85.9	86.1	87.3	87.9	88.8	88.8	87.2	88.6	87.6	87.9	87.2	85.7	88.8
1962	84.2	85.3	86.1	88.7	90.2	90.1	88.9	88.9	87.4	87.1	88.8	87.2	90.2
1963	87.2	88.2	86.9	88.7	88.3	88.5	87.3	89.7	88.9	88.8	87.4	85.6	89.7
1964	85.1	87.1											
5 yrs.	87.2	88.2	87.3	89.0	90.2	90.1	90.0	91.0	90.1	88.9	88.8	87.2	91.0

FIG. 5 DAILY MAXIMUM TEMPERATURE (°F) WATERFORD BARBADOS

(March 1959 - February 1964)



on 1st March 1962. Figures for monthly mean daily minimum temperature and absolute minimum temperature are given in Tables 4 and 5, and the graphs showing their seasonal variation in Fig. 6.

Diurnal Temperature Range*

The annual average of diurnal temperature range is 14.5° F. Its seasonal variation (Fig. 7) shows the highest range in FEBRUARY (16.7° F) and the lowest in JULY (12.4° F). It also shows a sudden drop of average diurnal range from APRIL to JUNE. The pattern of its seasonal variation is an inversion of that of the absolute minimum temperature as shown in Fig. 8. Figures for monthly mean diurnal temperature range are given for the 5 year period in Table 6.

0900 hrs. and 1600 hrs.** Dry Bulb Temperatures

The annual average temperature for 0900 hrs. and 1600 hrs. are 82.1° F and 82.3° F respectively. There is little difference in their annual average and seasonal variation except in FEBRUARY when they differ by 1.6° F. Both 0900 hrs. and 1600 hrs. temperatures are highest in AUGUST (83.7° F. and 83.8° F. respectively) and lowest in FEBRUARY (79.6° F) and JANUARY (80.6° F) respectively. There is a second maximum in JUNE (83.4° F) for both 0900 hrs. and 1600 hrs. Figures for monthly means of 0900 hrs. and 1600 hrs. temperatures are given in Tables 7 and 8. Also their seasonal variations are shown in Fig. 9.

* Refer to Appendix 2.

** All times refer to Eastern Standard Time.

TABLE 4 MONTHLY MEAN DAILY MINIMUM TEMPERATURE (°F) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959				72.0	71.0	75.0	72.0	73.0	72.1	72.2	71.6	70.8	
1960	68.1	66.3	68.9	71.6	72.7	74.1	74.3	73.9	71.9	73.5	70.7	69.1	71.3
1961	69.6	68.4	68.6	70.1	74.4	74.4	73.8	74.8	72.3	72.6	72.0	69.6	71.7
1962	70.2	69.2	67.5	70.3	72.0	74.4	74.2	73.1	72.7	71.3	70.3	70.3	71.3
1963	68.9	67.9	70.9	69.9	72.6	75.0	74.1	73.2	72.4	71.6	71.7	70.1	71.5
1964	67.2	66.5	71.1	71.8									
AVR.	68.8	67.7	69.4	70.8	72.5	74.6	73.7	73.6	72.3	72.2	71.3	70.0	71.4

TABLE 5

ABSOLUTE MINIMUM TEMPERATURE (°F) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			65.0	67.0	68.0	71.0	68.0	66.0	68.3	67.9	68.5	67.0	
1960	62.1	62.3	62.8	67.1	68.1	70.5	70.8	66.9	67.3	69.2	66.1	62.0	62.0
1961	63.3	62.1	64.3	66.5	68.1	70.0	70.5	70.8	68.2	68.1	68.0	63.1	62.1
1962	63.9	63.9	59.4	64.9	67.5	70.3	69.6	68.9	66.9	67.9	65.0	62.8	59.4
1963	63.2	60.1	63.8	63.7	69.0	70.9	68.9	70.0	67.9	68.5	67.2	63.0	60.1
1964	61.0	61.0											
ABS.	61.0	60.1	59.4	63.7	67.5	70.0	68.0	66.0	66.9	67.9	65.0	62.0	59.4

FIG. 6 DAILY MINIMUM TEMPERATURE (°F) WATERFORD BARBADOS

20

(April 1959 - March 1964)

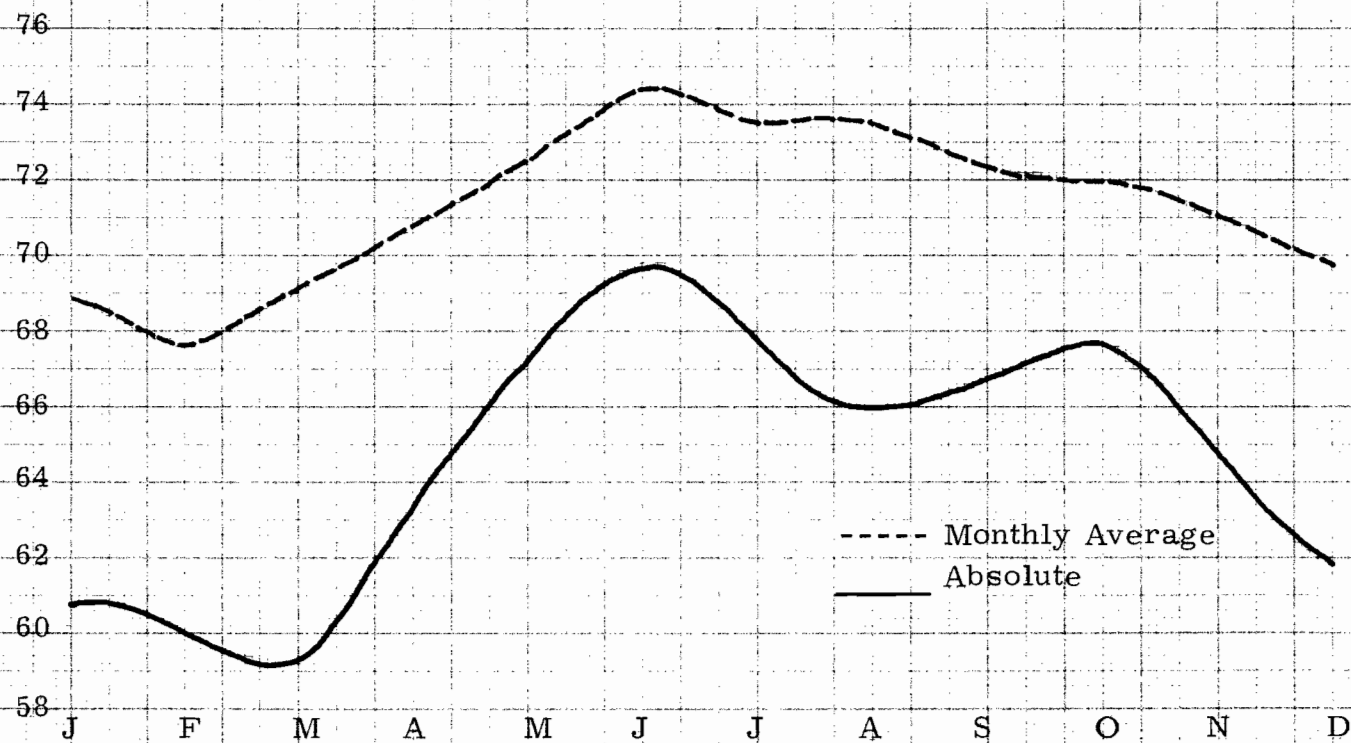


FIG. 7 DIURNAL RANGE OF TEMPERATURE (°F) WATERFORD BARBADOS

21

(April 1959 - March 1964)

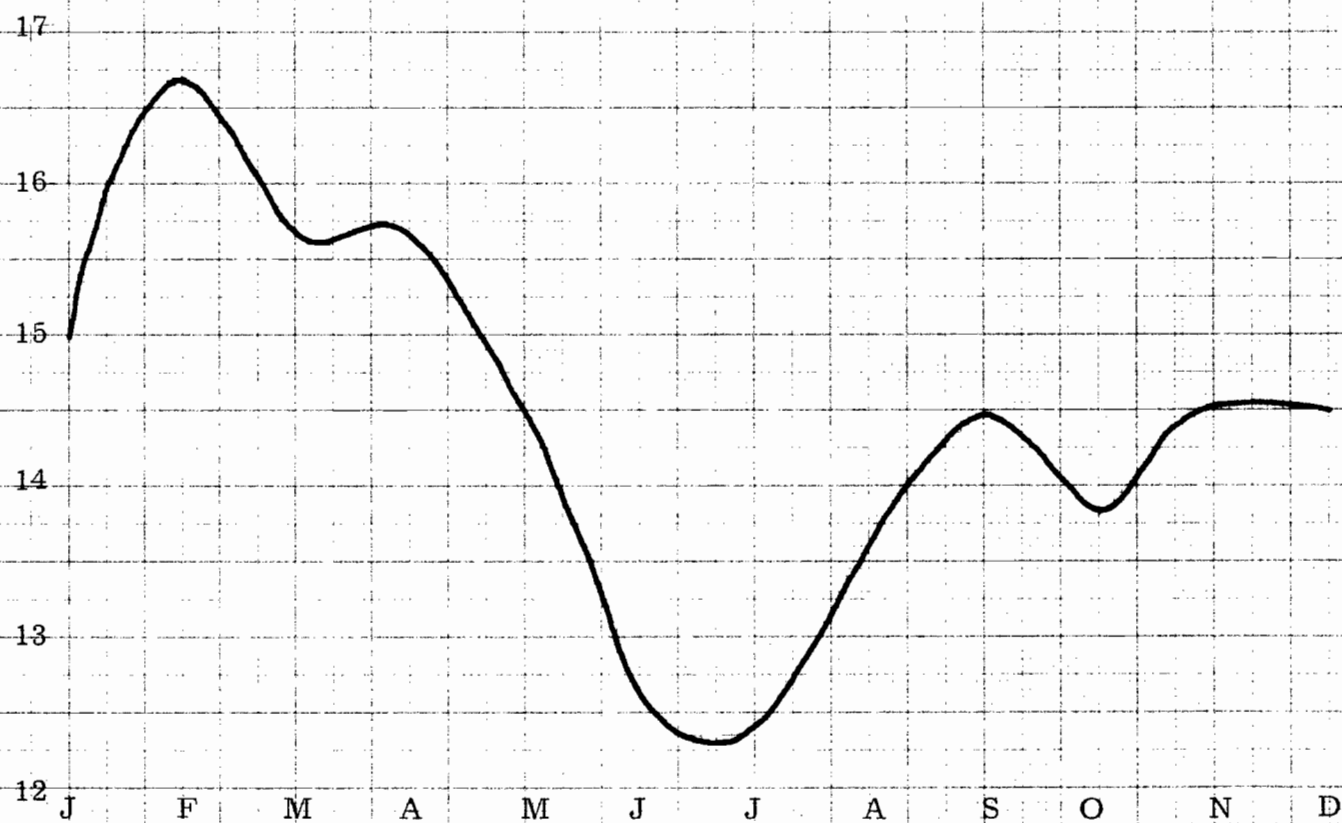


FIG. 8 DIURNAL RANGE OF TEMPERATURE AND ABSOLUTE MINIMUM
TEMPERATURE (°F)
WATERFORD BARBADOS

22

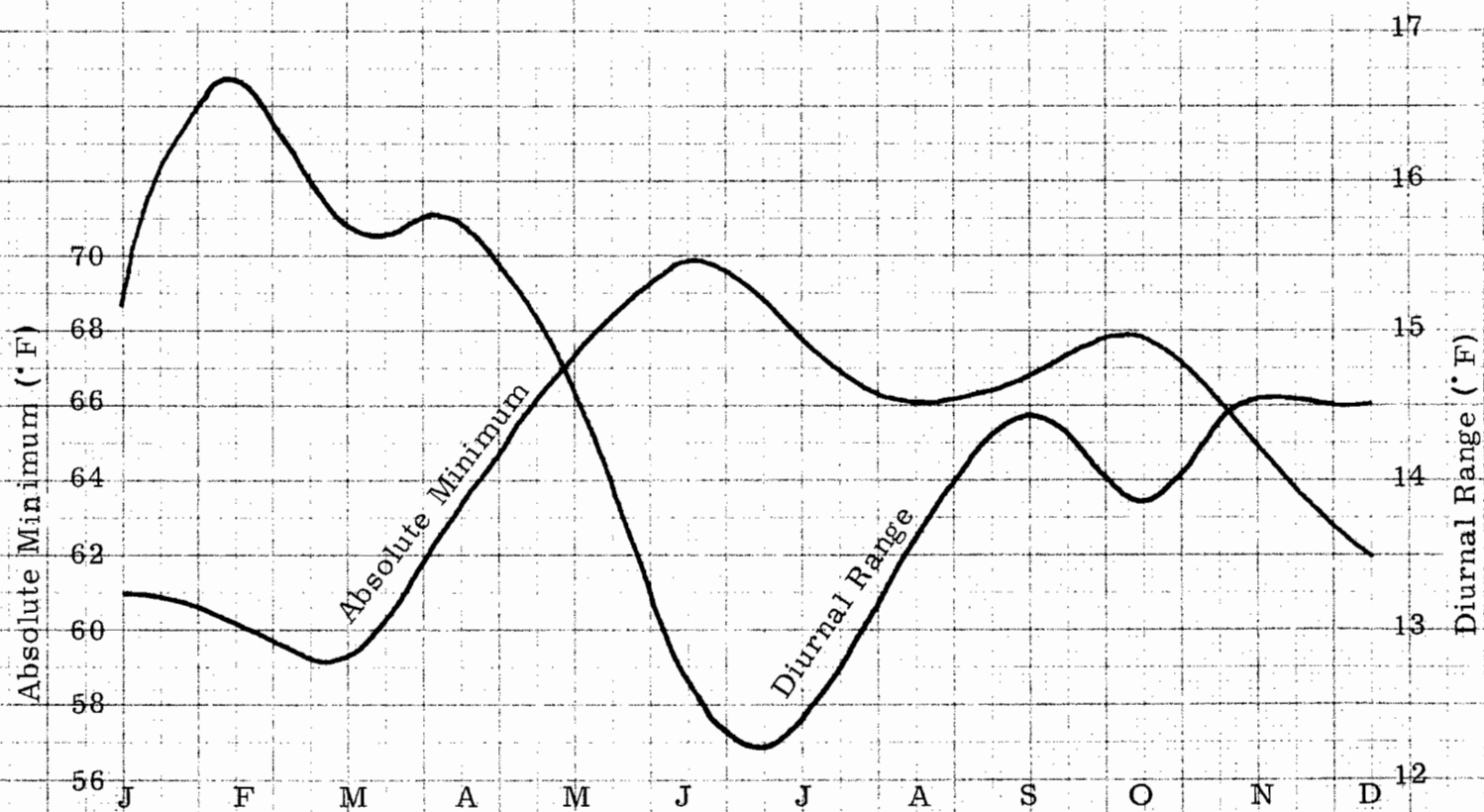


TABLE 6 MONTHLY MEANS OF DIURNAL TEMPERATURE RANGE (°F) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959				14.0	15.0	13.0	15.0	16.0	15.9	13.8	13.8	14.9	
1960	16.5	18.5	16.4	14.3	14.4	12.9	12.0	12.5	15.2	12.8	16.0	15.5	14.7
1961	14.9	16.2	16.9	16.6	12.9	13.0	11.7	12.1	14.1	12.5	13.7	14.1	14.1
1962	12.4	13.8	17.3	16.5	15.9	12.3	12.3	13.5	12.8	14.5	15.3	13.9	14.2
1963	15.0	17.2	14.2	17.2	14.1	11.5	11.3	14.2	14.4	15.1	14.1	14.2	14.4
1964	16.3	18.3	15.0										
AVR.	15.0	16.8	15.7	15.7	14.5	12.5	12.4	13.7	14.5	13.8	14.5	14.5	14.5

TABLE 7 DRY BULB TEMPERATURE, 0900 HRS. WATERFORD, BARBADOS
(°F)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959				82.0	82.0	83.0	83.0	85.0	84.2	82.5	82.3	81.8	
1960	80.6	80.2	80.9	82.2	83.6	83.7	82.8	83.7	84.1	82.9	83.4	81.1	82.4
1961	80.5	79.4	81.2	82.3	83.2	83.3	82.1	83.1	83.0	81.4	82.0	80.5	81.8
1962	78.6	78.6	80.7	82.6	84.1	83.3	83.1	83.1	82.5	83.4	82.6	81.4	82.0
1963	79.6	80.0	81.3	83.1	82.7	83.5	81.9	83.8	82.8	83.6	82.6	81.2	82.2
1964	79.5	80.0	81.6										
AVR.	79.8	79.6	81.1	82.4	83.1	83.4	82.6	83.7	83.3	82.8	82.6	81.2	82.1

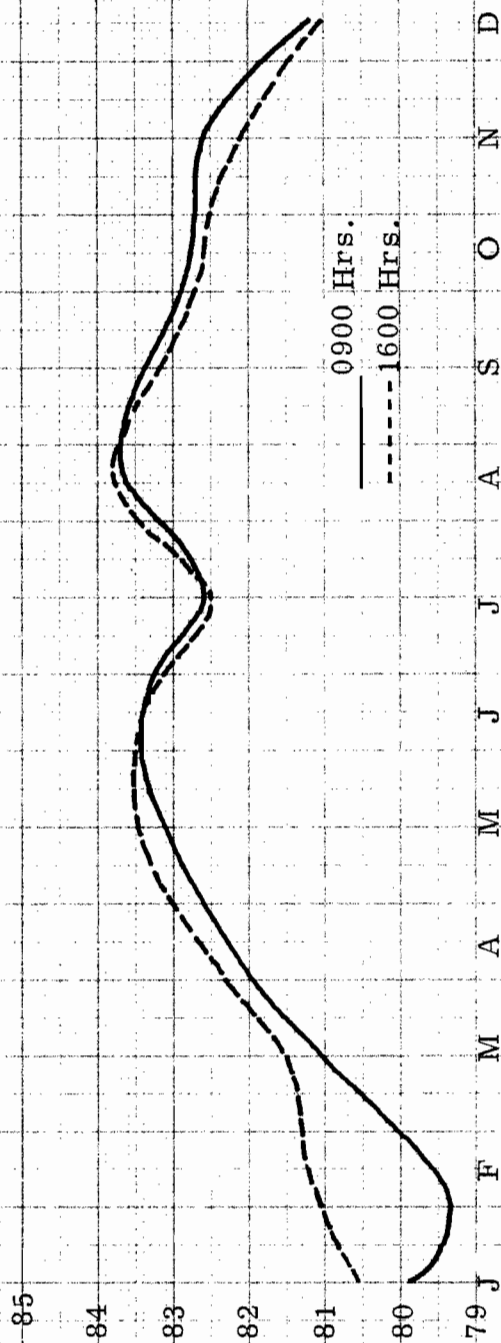
TABLE 8 DRY BULB TEMPERATURE, 1600 HRS. WATERFORD BARBADOS
(°F)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960	80.9	84.2	81.2	82.2	83.7	83.4	82.9	83.3	83.6	82.8	82.7	81.2	82.7
1961	81.4	80.5	81.8	82.4	83.2	83.4	81.9	83.5	83.3	81.3	81.6	80.6	82.1
1962	79.5	78.7	81.1	83.0	84.3	83.1	82.9	83.6	82.6	83.1	82.3	80.8	82.1
1963	80.6	81.6	81.8	83.2	82.4	83.6	82.4	84.7	83.4	83.0	81.7	81.2	82.5
1964	80.6	81.3	82.4	82.8									
AVR.	80.6	81.2	81.5	82.7	83.4	83.4	82.5	83.8	83.2	82.6	82.1	81.0	82.3

(SECRET)

FIG. 9 DRY BULB TEMPERATURE (°F) 0900 HRS. & 1600 HRS.
WATERFORD, BARBADOS

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The above dry bulb temperature data at the two fixed hours give no information about the daily course of temperature. If observations were made three times a day, one in the morning, one in the afternoon, and one in the evening, a fairly good idea of the diurnal variation could have been obtained. However, such information can be obtained from thermograph records, which though available for Waterford, have not been analysed in this thesis.

Relative Temperature

Though the annual course of daily mean temperature for Waterford is given by the curve in Fig. 4 and by figures in Table 1, and also described on page 10, the comparison of such annual course of temperature with that of another place may not be easy. Two problems present themselves. Firstly, the average annual temperature of the two places may be different; it then becomes difficult to compare fluctuations about different averages. Secondly, the annual amplitude of the annual course or the annual range, may be different for the two places, making it still more difficult to make comparisons of the annual course.

The two obstacles are eliminated by the method of relative temperatures*. This concept was introduced by W. Köppen, and it makes the comparison of annual course of temperature in different places easy. Figures of relative temperature in percentage for Waterford are given in Table 9. According to the definition, the relative temperature of the

* Refer to Appendix 2.

TABLE 9 RELATIVE TEMPERATURE (%)

Month	Waterford	Codrington	Seawell	Joe's River	Binfield
Jan	8	9	0	0	16
Feb	0	0	5	6	0
Mar	19	32	24	19	14
Apr	53	64	57	69	33
May	76	95	94	90	81
June	100	100	100	97	81
July	79	91	89	88	86
Aug	89	95	94	100	96
Sept	70	91	94	94	100
Oct	62	77	84	97	88
Nov	51	64	65	59	70
Dec	21	34	35	41	46

coldest month is always 0%, and that of the warmest month always 100%.

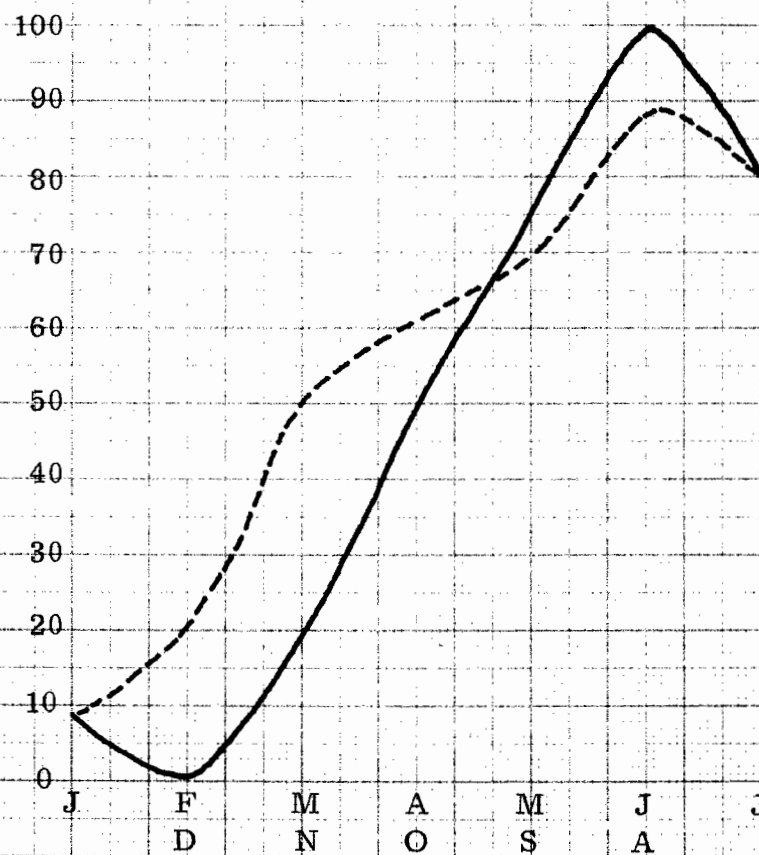
A graphical representation of relative temperatures makes it easier to compare different series of relative temperatures. This presentation was first introduced by V. Conrad (1941a). Fig. 10 shows the annual course of relative temperature for Waterford in graphical representation. The relative temperature for the first seven months are plotted as ordinate, and the months at equal intervals to the right on the horizontal axis. The curve then turns back to the left, starting from July, and showing the values of the other months. The curve of relative temperatures from January to July is shown by a full line, while that for the second half of the year is shown by a broken line.

In Fig. 10 the phase^{*} of the annual course of temperature is clearly indicated, the minimum temperature occurring in February, and the maxima occurring in June and August as already stated (page 10). The curve brings out clearly also the asymmetry in the annual course; temperature is seen to rise more rapidly in the first half of the year but falls less rapidly in the second half; also January, February and March and April are seen to be colder than their corresponding months after July, while May and June are warmer than their corresponding months.

The usefulness of relative temperatures and their graphical presentation become more evident when the annual course of temperature

FIG. 10 RELATIVE TEMPERATURE (%) WATERFORD, BARBADOS
(March 1959 - February 1964)

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in Waterford is compared with those of other places in Barbados (page 53).

Continentality

The extent to which the climate of a place, especially the temperature conditions, is affected by the land mass is called "Continentality." The most striking effect of the continental surface on the climate is the increase of the annual range of temperature inland. The annual range of temperature, A , is therefore taken to be the measure of continentality; but it also increases with increasing latitude, owing to the increase of the annual variation of insolation towards the poles. The measure of continentality is therefore taken to be $A/\sin \phi$. The formula frequently used (W1. Gorczynski, 1920) is as follows:

$$k = 1.7A/\sin \phi - 20.4$$

where k is the coefficient of continentality in %

A is the annual range of temperature in °C

ϕ is the geographic latitude

A coefficient of 100% means that the climate is influenced entirely by the land mass, while a coefficient of 0% means that the land mass has no influence on the climate, i.e. the climate is oceanic. It turns out that in some regions, including Barbados, the coefficient is negative, i.e. a "negative continentality," an expression which has no physical meaning. This is a weak point of this formula. However, a more serious weak point about this formula is that the coefficient of continentality becomes

infinite at the equator. V. Conrad has shown that the formula is not applicable within the belt of the Tropics between 10°N and 10°S (Conrad and Pollak, 1962).

O.V. Johanson (V. Conrad, 1962) has proposed a modification of the above formula, which avoids this drawback. His formula is as follows:

$$k = 1.7A / \sin(\phi + 10) - 14$$

It turns out that neither the original formula nor the modified one is suitable for Barbados. Both give negative coefficients for the continentality of five stations in Barbados. Table 10 gives the latitude, the height above sea level, distance from the ocean, and the coefficient of continentality of the stations.

Though the negative values are undesirable, the results give useful information. The coefficients, using both formulae, show that some stations have less oceanic climate than others. The stations have been arranged in the increasing order of continentality, or decreasing order of "oceanicity." The stations nearest to the coast have more oceanic climate. Though Binfield is nearer to the coast than both Codrington and Waterford, its climate is least oceanic. This may be due to its high altitude which has a tendency of increasing the variability of weather, and hence the continentality (Landsberg, 1962).

TABLE 10

COEFFICIENT OF CONTINENTALITY BARBADOS

Station	Latitude	Ht. above sea level (ft)	Distance from Ocean (Stat. Mls)	Original Formula	^k Modified Formula
Joe's River	13° 12' N	430	1	-7.0	-6.4
Seawell Airport	13° 05' N	130	3/4	-4.9	-5.1
Codrington	13° 07' N	180	1-3/4	-4.1	-4.7
Waterford	13° 07' N	120	2	-0.7	-2.8
Binfield	13° 11' N	1040	1-1/4	+3.1	-0.3

Interdiurnal Variability

The interdiurnal variability of temperature, IDV, is a measure of changes in temperature from day to day. It takes into account, not only the quantity of the element, but also its sequence from day to day. They are computed either (i) as differences of the consecutive daily mean temperatures, or (ii) as differences of temperature at a fixed hour of consecutive days. The definition may be put in the form,

$$IDV = \sum_{i=1}^{i=n} |T_i - T_{i+1}| / (n-1)$$

where T is the daily mean temperature, or temperature at
fixed hour of the day

n is the no. of items of the element.

One of the advantages of computing the IDV is that it converges rapidly towards a true mean, so that five years records and sometimes even three years records will be accurate enough to reveal its main features (Landsberg, 1962). There might therefore be some justification in presenting calculations of IDV for Waterford during the four year period, 1960-1963.

Fig. 11 shows the annual course of the average IDV for Waterford. The months of relatively large temperature fluctuations are JANUARY (1.50° F), MARCH (1.48° F), and DECEMBER (1.47° F). The months of relatively small temperature changes are OCTOBER (0.90° F), and NOVEMBER (1.06° F). The rest of the months have values hovering around 1.20° F. The annual average is 1.23° F. Table 11 gives figures for the annual course.

FIG. 11

INTERDIURNAL TEMPERATURE VARIABILITY (°F)
WATERFORD BARBADOS

(1960 - 1963)

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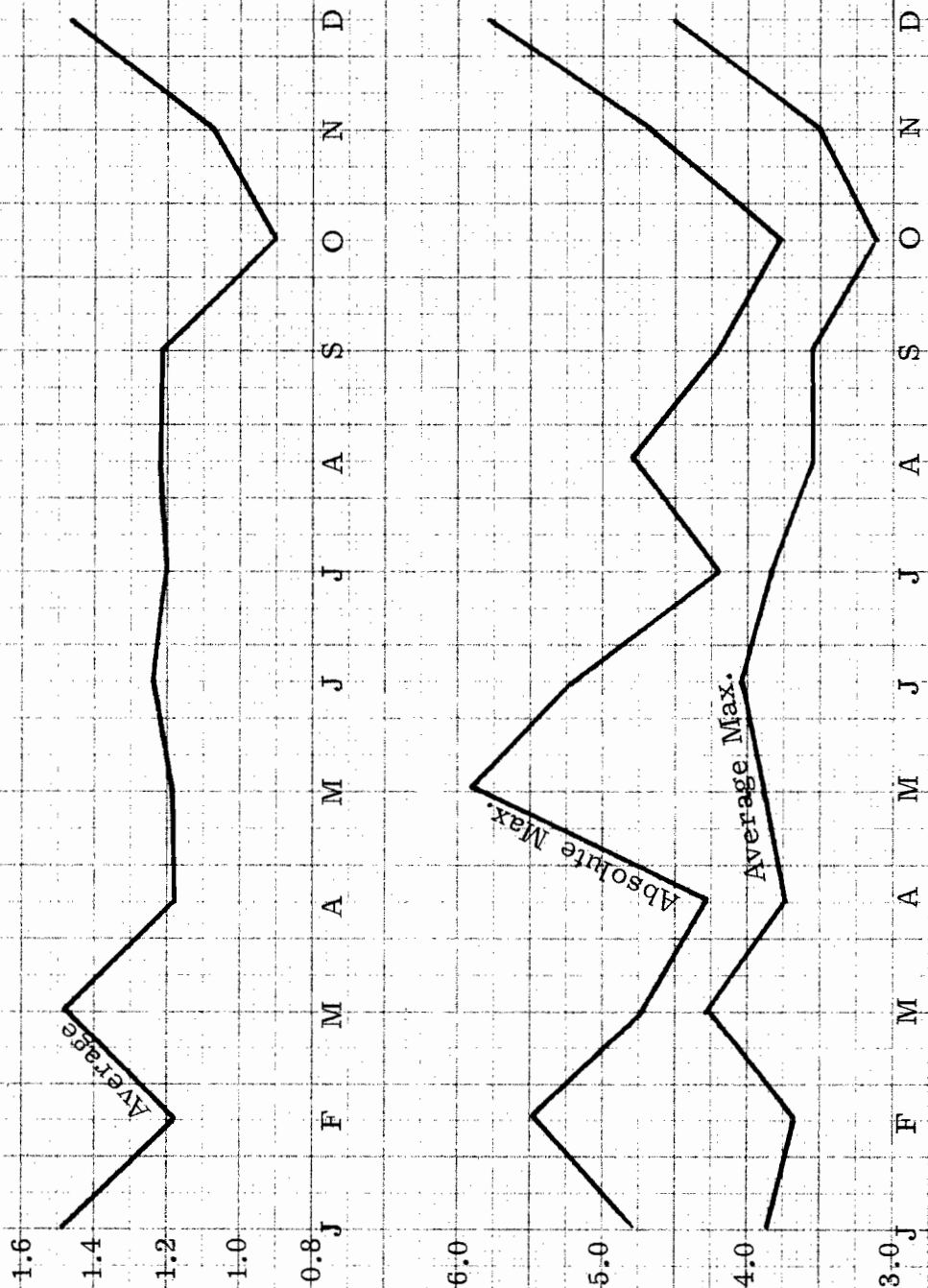


TABLE 11 INTERDIURNAL TEMPERATURE VARIABILITY (°F)

WATERFORD (1960-1963)

Month	Average	Average Maximum	Absolute Maximum
Jan	1.50	3.92	4.8
Feb	1.18	3.70	5.5
March	1.48	4.28	4.7
April	1.18	3.78	4.3
May	1.18	3.90	5.8
June	1.24	4.08	5.2
July	1.20	3.85	4.2
Aug	1.21	3.62	4.8
Sept	1.20	3.58	4.2
Oct	0.90	3.15	3.8
Nov	1.06	3.52	4.7
Dec	1.47	4.55	5.7
Annual	1.23	3.83	5.8
Years of Average	4	4	4

Fig. 11 also gives the annual course of the average maximum IDV, i.e. the maximum interdiurnal temperature change that occurs in each month averaged over the four year period. The average maximum IDV varies from the highest of 4.55°F in DECEMBER to a lowest of 3.15°F in OCTOBER. The annual maximum is 3.82°F . The annual course follows more or less the same pattern as that of the average IDV. Fig. 11 also shows the annual course of the absolute maximum IDV for the four year period. The largest change for the whole period was -5.8°F , recorded on 27th May, 1962. The next largest was -5.7°F on 12th December, 1960, and $+5.5^{\circ}\text{F}$ on 29th February, 1960.

The above analysis shows that the general trend of the annual course of average IDV indicates relatively high values in the dry season (Northern Hemisphere Winter), and low values in the rainy season (Northern Hemisphere Summer and Autumn). This is in agreement with the behaviour of this element in most places, although its magnitude may be small in Barbados. Landsberg states, "this indicator of the instability of weather shows its largest variation in the interior of the continents and becomes less the closer the station is to the ocean. The variations are usually larger in Winter than in Summer and, as an approximate rule, it can be stated that: The interdiurnal temperature changes are twice as high during the cold season as during the warm season." (Landsberg, 1962).

The frequency of such occurrences reveal more interesting features. In Table 12 the average frequency of occurrence, (expressed in the no. of days per month), of interdiurnal temperature change is given in seven steps of temperature change, including no change. The most frequent change occurs in the interval $0.1^{\circ}\text{F} - 1.0^{\circ}\text{F}$ for all months except MARCH, when it occurs in the interval $1.1^{\circ}\text{F} - 2.0^{\circ}\text{F}$. The frequencies fall off rapidly with increasing temperature change. Fig. 12 gives the frequencies in graphical form, with the frequencies plotted at the midpoints of the various intervals. Frequencies for no change are entered in brackets.

The importance of such frequencies cannot be overemphasized. Landsberg notes, "The frequency of such occurrences, therefore, is of particular importance in judging the environment of man. This is important since medical investigations, as those of W.F. Petersen, have shown how these sudden weather changes precipitate and influence diseases. Because of large differences experienced for the unperiodic temperature variations in various parts of a country or continent, a close study is desirable to find suitable places for the establishment of sanitariums and health resorts." (Landsberg, 1962).

In order to have an idea of the sign of the temperature changes, separate calculations have been made for the average amount of temperature increase from day to day, termed, "warming," and the

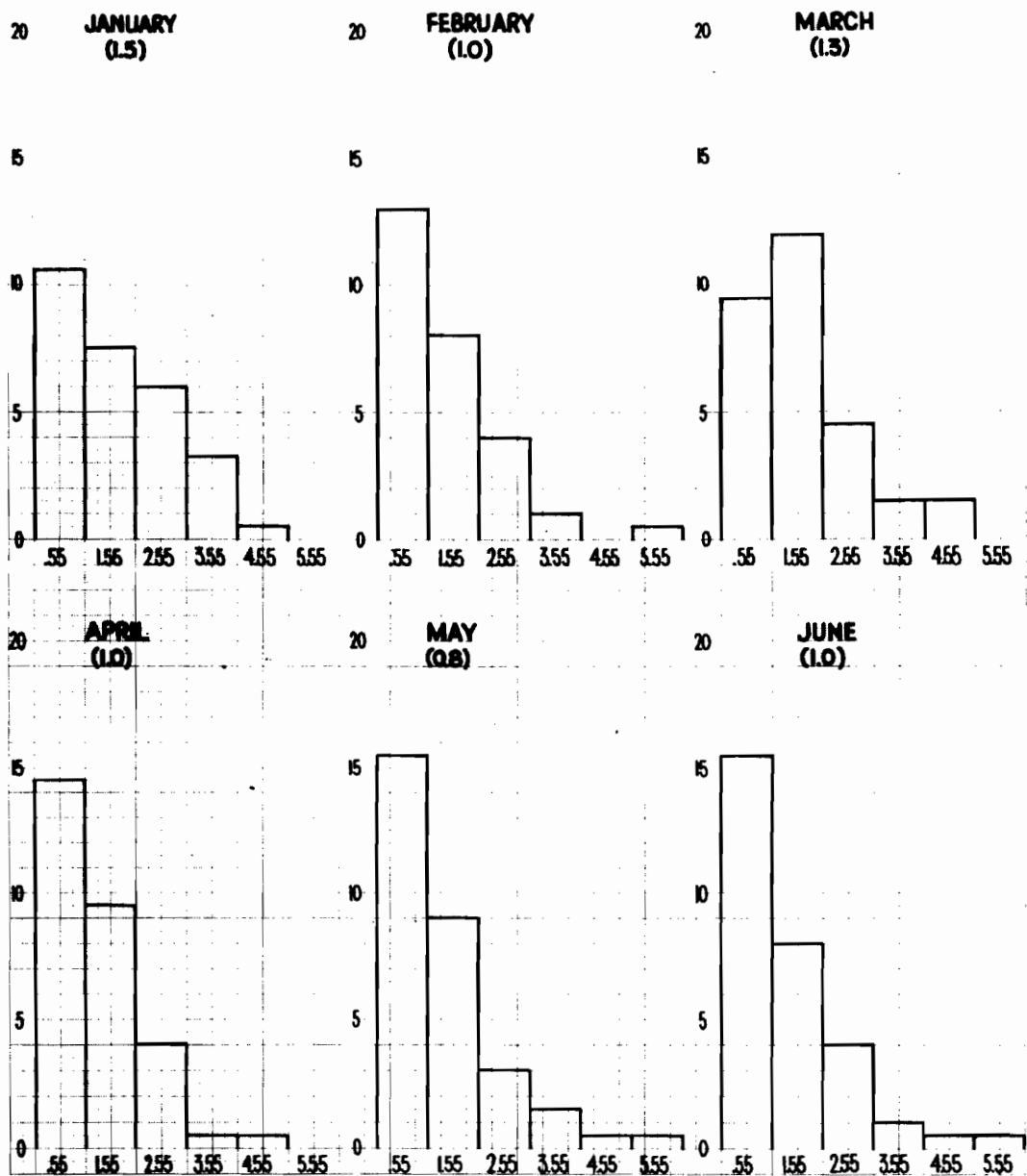
TABLE 12 AVERAGE FREQUENCY (NO. OF DAYS PER MONTH)
OF INTERDIURNAL TEMPERATURE VARIABILITY
WATERFORD (1960 - 1963)

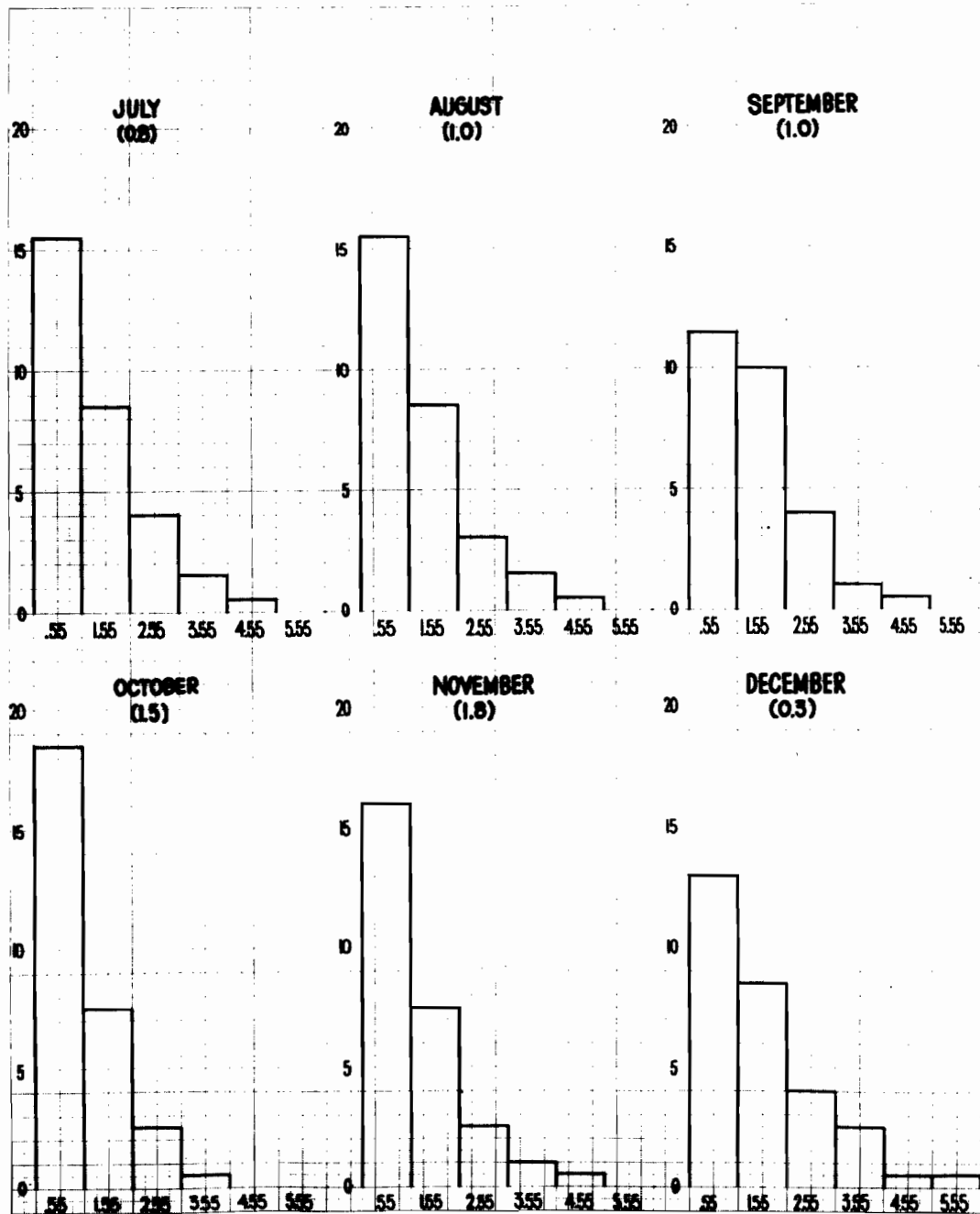
Month	0°F	0.1°F- 1.0°F	1.1°F- 2.0°F	2.1°F- 3.0°F	3.1°F- 4.0°F	4.1°F- 5.0°F	5.1°F- 6.0°F
January	1.5	11.2	7.5	6.0	3.3	0.5	0.0
February	1.0	13.1	7.8	3.8	1.0	0.0	0.3
March	1.3	9.5	12.1	4.5	1.3	1.3	0.0
April	1.0	14.6	8.6	3.8	0.5	0.5	0.0
May	0.8	15.3	9.0	2.8	1.5	0.3	0.3
June	1.0	15.3	8.0	3.9	1.0	0.5	0.3
July	0.8	15.3	8.3	3.8	1.3	0.5	0.0
August	1.0	15.5	8.5	3.0	1.5	0.5	0.0
September	1.0	11.3	10.0	4.0	1.0	0.3	0.0
October	1.5	18.5	7.2	2.3	0.5	0.0	0.0
November	1.8	15.9	7.5	2.5	1.0	0.3	0.0
December	0.3	12.9	8.5	3.8	2.5	0.5	0.5

FIG. 12

AVERAGE FREQUENCY (NO. OF DAYS PER MONTH) OF INTERDIURNAL TEMP. VARIABILITY

WATERFORD
(1960-1963)





average amount of temperature decrease, termed "cooling." (Figs. 13 and 14 and Tables 13 and 14). Annual average warming (1.29°F) is about the same as the annual average cooling (1.32°F). Average warming exceeds average cooling in January, February, March, May and July; while average cooling exceeds average warming during the rest of the year. It may be added that such differences are small and do not exceed 0.3°F in any month.

In Figs. 13 and 14 and Tables 13 and 14 the annual average maximum warming and cooling are again about the same, 3.40°F and 3.39°F respectively. Average maximum warming occurs in January - May, and also in September, while average maximum cooling occurs during the rest of the year. The difference between the average maximum warming and cooling does not exceed 1.0°F in any month. The highest differences occur in April (0.96°F) and June (0.98°F). The absolute maximum warming exceeds the absolute maximum cooling for most part of the year.

Stability of 5-Year Average Temperatures

Because climatic elements often vary strongly with time, whether monthly, seasonal, or annual averages, it may be inquired whether the monthly averages and annual averages of temperatures for Waterford, based on five years records, are stable or whether they depart significantly from the long-term averages. Sometimes the departure can be considerable,

FIG. 13 WARMING (° F) WATERFORD BARBADOS (1960 - 1963)

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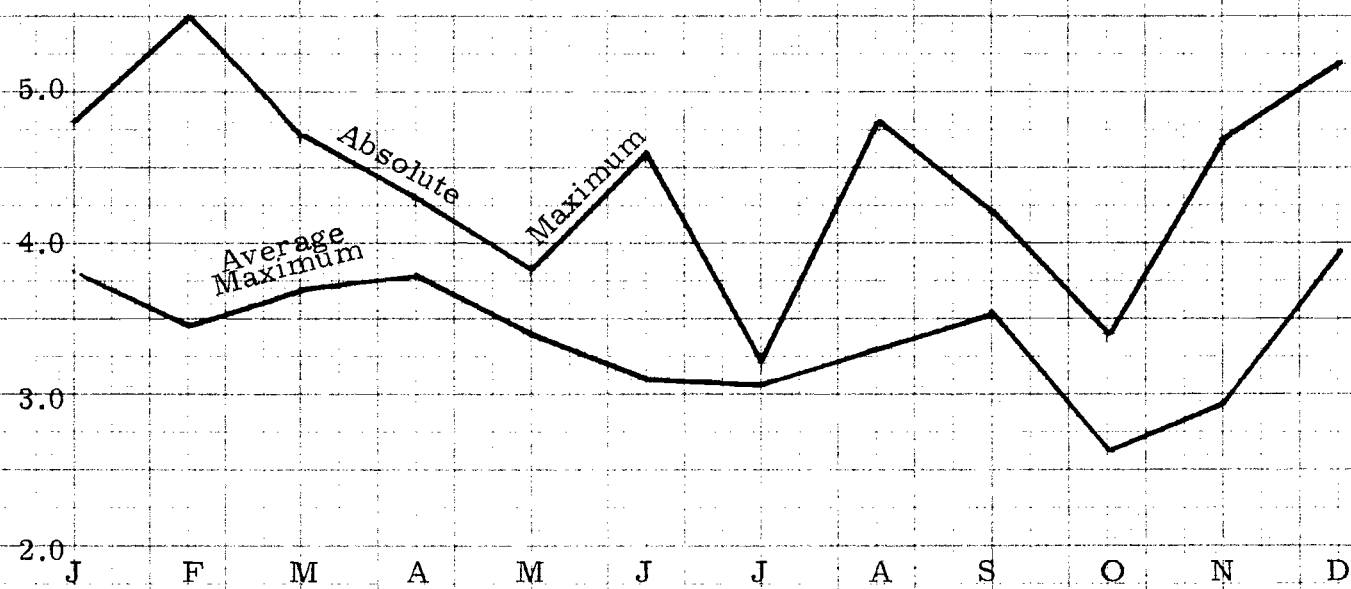
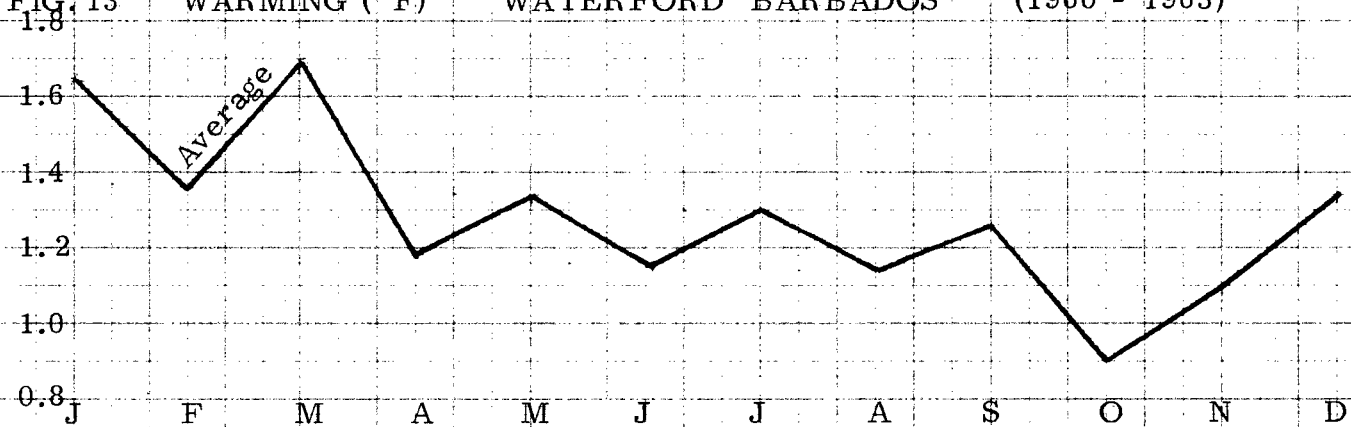


FIG. 14 COOLING (°F) WATERFORD BARBADOS (1960 - 1963)

44

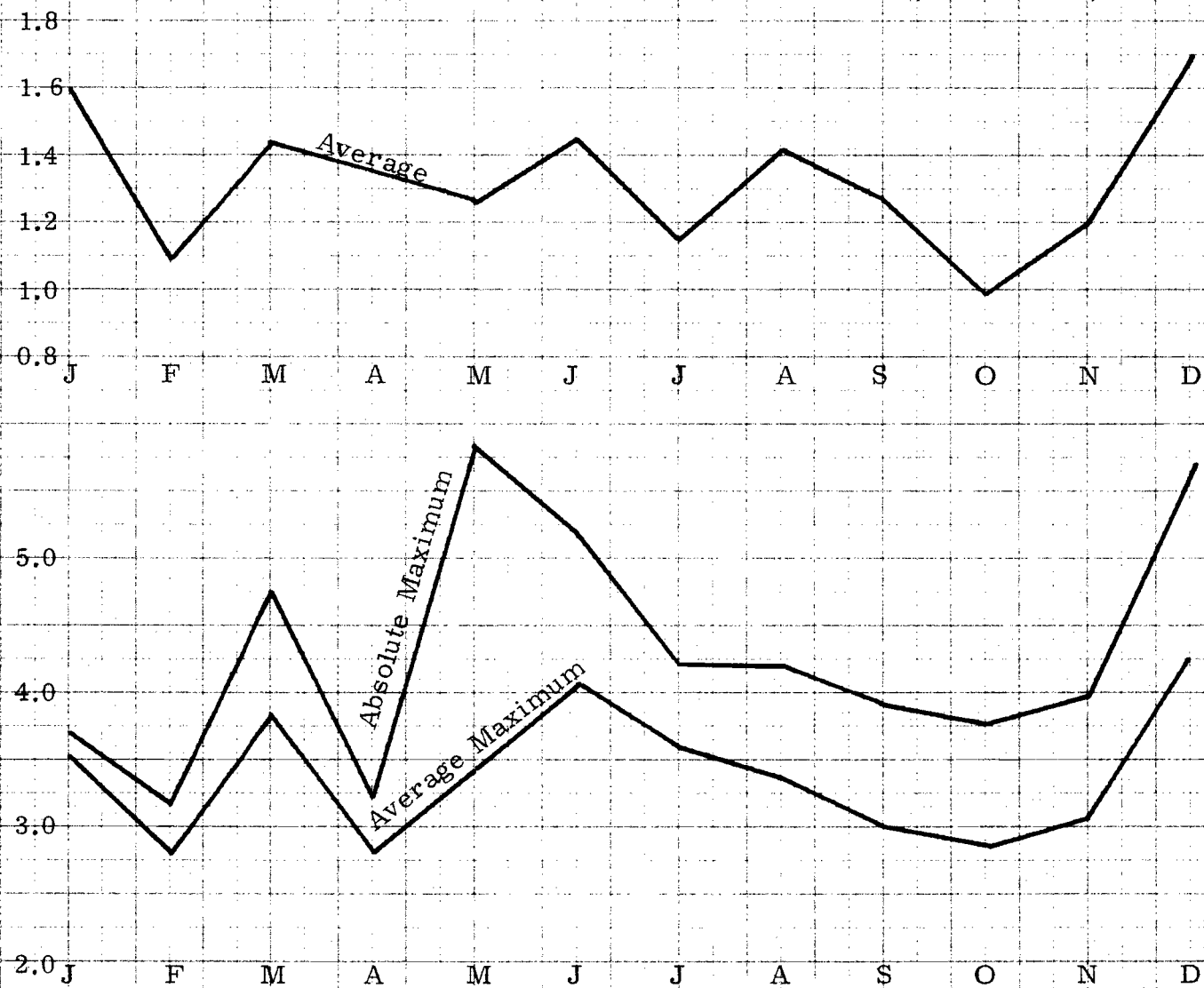


TABLE 13 WARMING (°F) WATERFORD (1960 - 1963)

Month	Average	Average Maximum	Absolute Maximum
Jan	1.65	3.82	4.8
Feb	1.37	3.48	5.5
March	1.71	3.68	4.7
April	1.19	3.78	4.3
May	1.34	3.40	3.8
June	1.16	3.10	4.6
July	1.30	3.08	3.2
Aug	1.14	3.32	4.8
Sept	1.26	3.58	4.2
Oct	0.91	2.62	3.4
Nov	1.10	2.95	4.7
Dec	1.34	3.98	5.2
Annual	1.29	3.40	5.5
Years of Average	4	4	4

TABLE 14 COOLING (°F) WATERFORD (1960 - 1963)

Month	Average	Average Maximum	Absolute Maximum
Jan	1.58	3.55	3.7
Feb	1.08	2.82	3.2
March	1.43	3.85	4.7
April	1.34	2.82	3.2
May	1.25	3.45	5.8
June	1.44	4.08	5.2
July	1.14	3.55	4.2
Aug	1.41	3.35	4.2
Sept	1.27	3.00	3.9
Oct	1.00	2.85	3.8
Nov	1.20	3.08	4.0
Dec	1.70	4.32	5.7
Annual	1.32	3.39	5.8
Years of Average	4	4	4

and any indiscriminate use of averages, whether for descriptive purposes, or in applied climatology, could be quite misleading. A knowledge of the required length of series to establish a stable average of an element is therefore essential; however, the length of series required varies with the place, season and the type of climatic element.

The variability of the element is a good indicator as to whether long or short records may be needed to establish a long-term average. The measure of variability used here is the relative variability.* Both the monthly means and the annual means of maximum and minimum temperatures did not vary much over the five year period, with a very slight relative variability ($<1\%$). However, five years records are too short to ensure that the above relative variability is representative of mean temperatures at Waterford.

Assuming that the variability of temperature is about the same in regions around Waterford Station, use was made of Seawell Airport (about 8 miles ESE of Waterford) temperature records which cover eleven years, (1953-1963) to calculate the relative variability. This assumption may be valid because the two stations are located in the same climatic region, according to Thorntwaite's classification (Rouse, 1962), they are not too distant apart and differ in altitude by only fifty feet above sea level (Conrad and Pollak, 1962). The relative variability turned out to be a little less than $1/2\%$ for annual mean temperatures and a little less

* Refer to Appendix 2.

than 1% for monthly mean temperatures. We conclude that the average temperatures at Seawell Airport, and therefore at Waterford, will not vary much with increasing no. of years of records, and that five year averages can reasonably be used for climatological purposes.

The above conclusion was tested by working out five year averages (1953-1957) and ten year averages (1953-1962) of maximum and minimum temperatures for Seawell Airport. The difference between the two averages was not more than 0.6° F in the case of monthly averages. The figures for the five year and ten year averages and their differences are given in Table 15. A further test was applied by making use of the method of differences* (Conrad and Pollak, 1962) to reduce the five year annual average temperatures for Waterford to ten year average by making use of Seawell Airport temperature data. The ten year annual average maximum temperature (reduced) for Waterford turned out to be 85.7° F as compared to the actual five year average of 85.9° F. Similarly, the reduced ten year annual average minimum temperature was 71.3° F as compared to the actual five year average of 71.4° F.

Stability of Extreme Values of Temperature

Extreme values of temperature, and in general, values of any climatic elements that occur only rarely, are known to depend upon the length of record. They tend to increase with increasing length of records. Birkeland and Frogner (1935) have shown theoretically that the range of

* Refer to Appendix 3.

TABLE 15 AVERAGE MAXIMUM TEMPERATURE (°F) SEAWELL AIRPORT

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
5 YR	83.1	83.0	84.1	85.3	86.3	86.4	85.7	86.4	85.8	85.8	85.2	83.9	85.1
10 YR	83.6	83.4	84.4	85.4	86.3	86.3	85.6	86.4	86.2	85.9	85.4	84.2	85.3
10 YR -5 YR	0.5	0.4	0.3	0.1	0.0	-0.1	-0.1	0.0	0.4	0.1	0.2	0.3	0.2

AVERAGE MINIMUM TEMPERATURE (°F) SEAWELL AIRPORT

5 YR	71.7	71.7	72.4	73.7	75.5	75.8	75.4	75.5	75.0	74.4	73.4	72.5	73.9
10 YR	72.0	71.5	72.8	74.1	75.6	76.0	75.4	75.5	74.9	74.9	74.0	73.1	74.2
10 YR -5 YR	0.3	-0.2	0.4	0.4	0.1	0.2	0.0	0.0	-0.1	0.5	0.6	0.6	0.3

extremes of temperature and rainfall increase with increasing length of records. Landsberg also states, "Extreme values in many observational series have statistical characteristics which make a rational treatment of such possible problems...distributions and procedures analogous to those for the normal distribution have been developed. Simplest among the procedures, and valid for a great many climatological series, is one developed by Gumbel." (Landsberg, 1962).

Five year records are too short to enable one to make such investigations. Gumbel feels that at least twenty years extremes are necessary in order to be able to use his method accurately (Landsberg, 1962). Probably the upper limits of absolute maximum and minimum temperatures at Waterford will not be very much different from the figures derived from the 5 year records (pages 13, 17). Nevertheless, they ought to be used with some caution, especially in the field of applied climatology.

Overall Temperatures of the Whole Island

As regards the average temperatures of the whole island, there are very few observations. Table 16 gives figures of monthly averages of daily mean temperatures for five stations. Codrington Agricultural Station has an annual average temperature of 78.7° F, the same as that of Waterford. Their seasonal variations are more or less the same, the annual range being 4.7° F at Waterford and 4.4° F at Codrington.

TABLE 16 MONTHLY AVERAGE TEMPERATURE (°F) BARBADOS

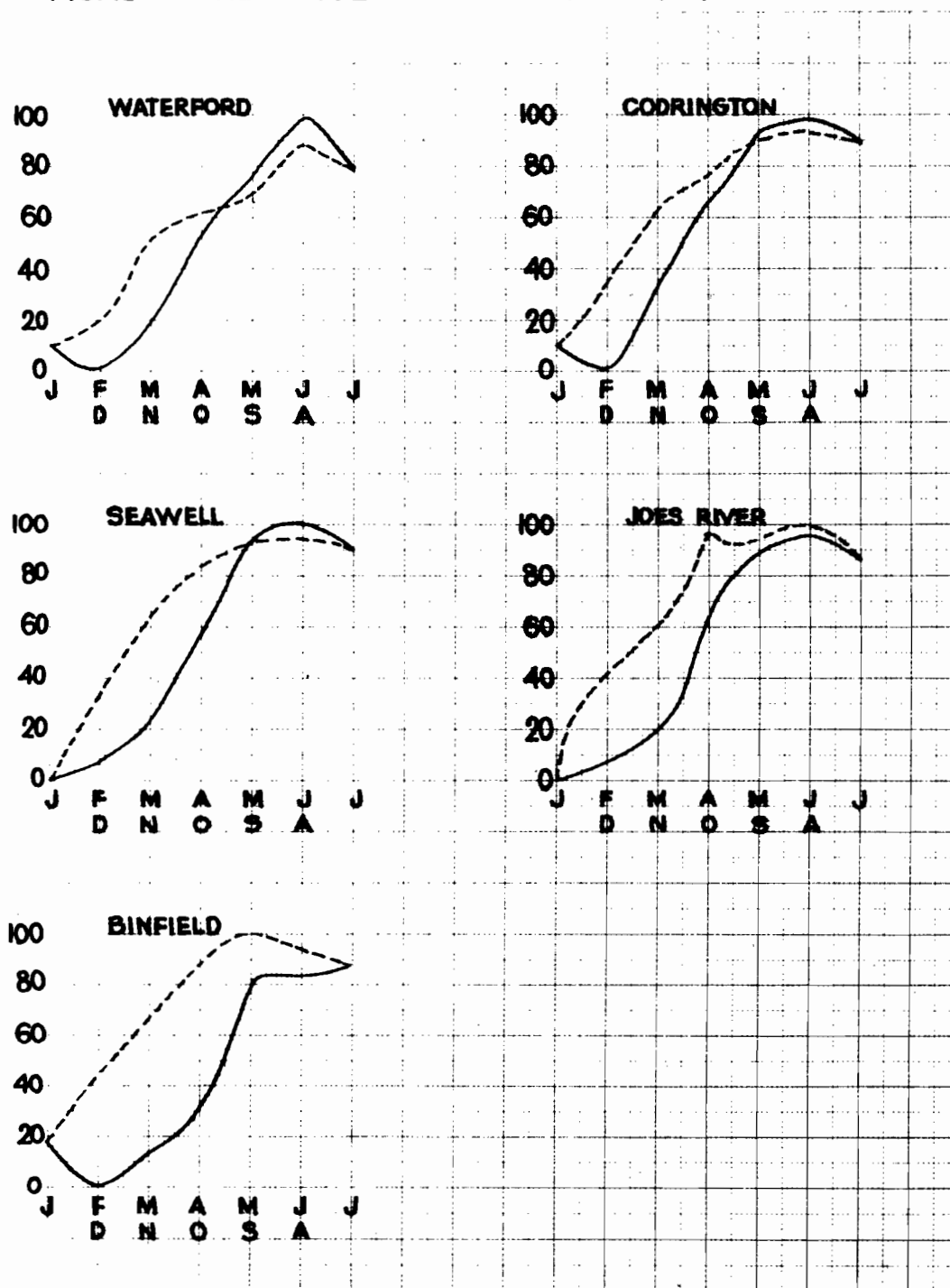
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANL.	YRS.
Codrington	76.3	75.9	77.3	78.7	80.1	80.3	79.9	80.1	79.9	79.3	78.7	77.4	78.7	54
Seawell	77.4	77.6	78.3	79.5	80.9	81.1	80.7	80.9	80.9	80.5	79.8	78.7	79.9	16
Waterford	76.6	76.2	77.1	78.7	79.8	80.9	79.9	80.4	79.5	79.1	78.6	77.2	78.7	5
Joe's River	74.4	74.6	75.0	76.6	77.3	77.5	77.3	77.6	77.4	77.5	76.3	75.7	76.4	8
Binfield	71.7	70.8	71.6	72.7	75.4	75.5	75.7	76.3	76.5	75.8	74.8	73.4	74.2	8

Seawell Airport's annual average temperature is 1.0° F higher than those of Waterford and Codrington. Also her monthly averages are 1.0° F higher, except in FEBRUARY, when they are about 2.0° F higher. The annual range of daily mean temperature is even lower (3.8° F). The strikingly similar annual course of the three stations is revealed by their relative temperatures presented in graphical form in Fig. 15.

It can be concluded that the spatial variation of temperature on the lowlands (i. e. 0-200 ft. elevation) is slight. All the three stations are below 200 ft. elevation and their temperatures can be taken to represent those of the lowlands, including the coastal areas.

Temperatures will, of course, vary significantly as one moves inland to the hilly areas. The annual average temperature of Binfield (altitude 1074 ft.) is less than that of Seawell Airport (altitude 130 ft.) by 5.7° F, while her monthly average temperatures do not fall below those of Seawell by more than 7.0° F in any month. Her annual range of temperature is 5.7° F. Joe's River (altitude 430 ft.) and about 3/4 of a mile from Binfield, has an annual average temperature which is 3.5° F less than that at Seawell. Its annual range is 3.2° F. Notice the slight resemblance between the annual course of temperature for Joe's River and Binfield. They both have their temperatures during the second half of the year warmer than the first half. It is more pronounced in the case of Binfield, at a higher altitude. It is probable that

FIG. 15 RELATIVE TEMPERATURES (%) BARBADOS



the annual course of temperature for Joe's River is representative of the pattern of the annual course of temperature in the middle lands (200 ft. - 800 ft.) and that of Binfield may be representative of the highlands (7800 ft.).

C.C. Skeete in "Weather Observations and Records in Barbados" (Skeete, 1934) writes, "The temperature in the highest parts of the island is usually 6° - 10° F lower than the temperatures in the lowlands and coastal districts." The highest peak in the island is 1,115 ft., on Mount Hillaby. Using the annual mean lapse rate of 5.0° F/1000 ft. as calculated by W.R. Rouse (1962), the annual mean temperatures in the highest parts of the highland should be about 6° F below those in the lowlands and coastal districts. In the case of monthly average temperatures, the highest in the island will be about 7.0° F below if we accept Rouse's range of monthly variation of lapse rate to be 6.1° F/1000 ft. to 4.2° F/1000 ft. during the course of the year. This is within the range given by Skeete.

II RAINFALL

Monthly and Annual Totals^{*}

The annual average rainfall is 42.29 ins. There is some variability from year to year of the annual total of rainfall for the five year period, but the length of record is so short as to render any valid assessment of the variability of rainfall doubtful.

There is significant distribution of the annual total of rainfall over the months. There are two pronounced maxima of monthly totals of rainfall. JULY is usually the wettest month with a monthly average of 7.37 ins., but the wettest month can occasionally be JUNE, SEPTEMBER or OCTOBER. A minor maximum occurs in SEPTEMBER or OCTOBER with an average monthly total of 6.16 ins. The driest month is APRIL with monthly average of 1.30 ins. FEBRUARY and MARCH also become the driest months occasionally.

JUNE to DECEMBER is the wet period and JANUARY to MAY the dry period. 81% of the annual rainfall falls within the wet period. Figures for monthly and annual totals of rainfall for the five year period are found in Table 17. Also a graph for seasonal distribution of rainfall is shown in Fig. 16

Rain Days^{**}

The number of raindays in the year is 219. The average number of raindays for each month is generally half a month or more, except in

* Refer to page 66.

** Refer to Appendix 2.

TABLE 17

MONTHLY TOTALS OF RAINFALL (INS.)

WATERFORD

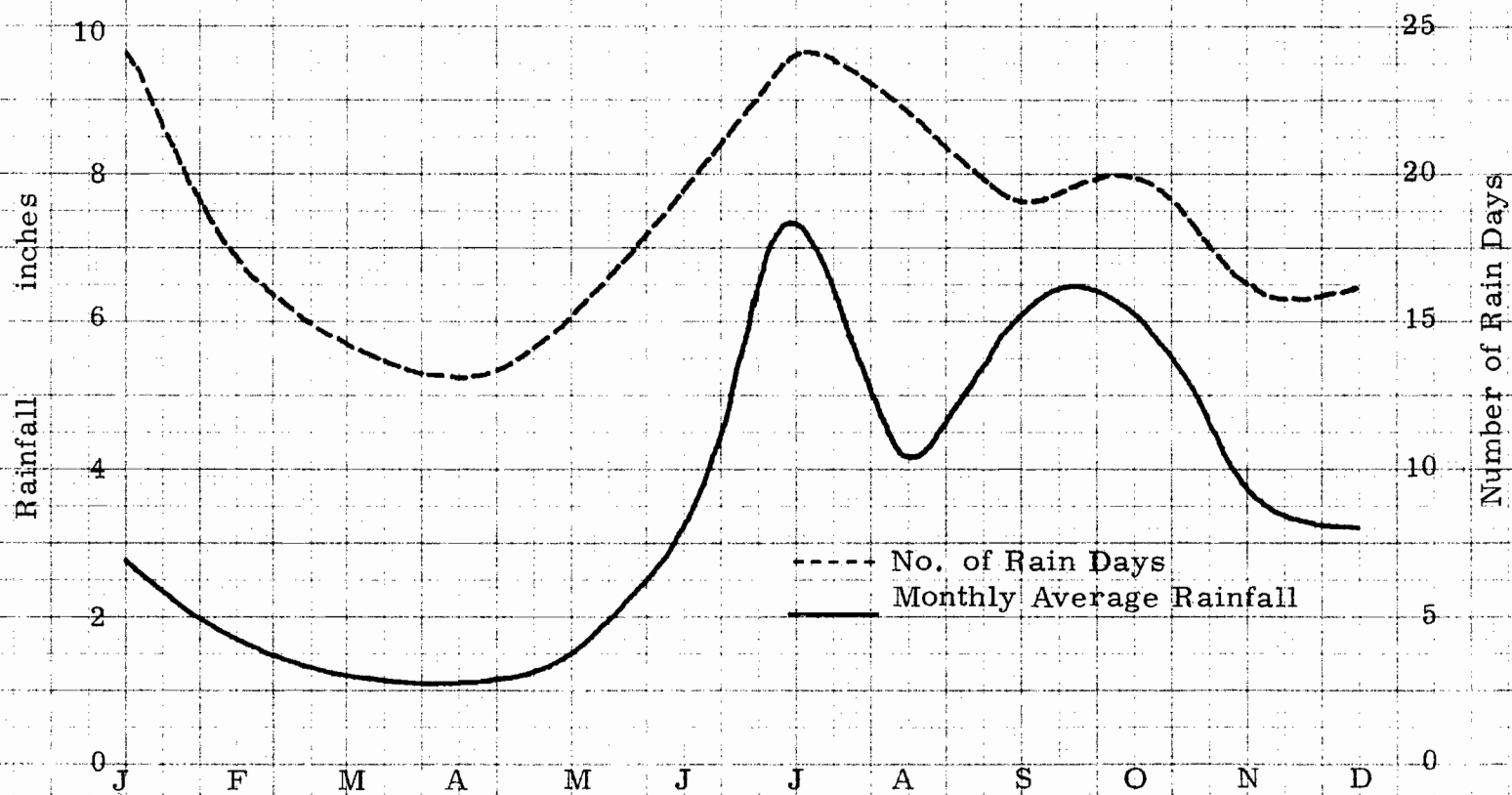
YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			1.33	3.20	1.34	1.29	2.71	1.89	6.00	9.84	4.38	2.20	
1960	1.99	2.12	2.31	1.34	1.66	3.31	7.52	5.70	2.68	3.90	0.85	2.80	36.18
1961	2.38	1.30	0.93	1.06	1.09	1.98	9.32	5.82	3.33	8.12	5.30	4.71	45.34
1962	3.15	1.51	0.74	0.43	1.04	7.31	4.31	4.30	7.35	4.85	2.91	4.08	41.98
1963	3.25	1.26	1.55	0.47	1.76	5.51	12.98	3.08	11.21	4.34	4.65	1.99	52.05
1964	0.98	0.72											
AVR.	2.35	1.38	1.37	1.30	1.38	3.88	7.37	4.16	6.11	6.21	3.62	3.16	42.29

FIG. 16

AVERAGE RAINFALL AND NO. OF RAIN DAYS WATERFORD BARBADOS

(March 1959 - February 1964)

57



MARCH and APRIL when monthly averages are fourteen days and thirteen days respectively. JANUARY and JULY have the highest number of rain days (24). It appears from the data on average rain days that Waterford Station is rainy all the year round. This certainly leads to a false picture of her rainfall regime. We must take into consideration also the amount of rainfall within each rainy day, i.e. the average intensity (ins./day). Table 18 gives the number of rain days in each month and Fig. 16 shows graph of the seasonal variation of number of rain days.

Rainfall Intensity *

The average intensity (ins./rainy day) is high in JULY, SEPTEMBER and OCTOBER and low in JANUARY to MAY (Table 18). This information throws light on the type of rain that falls in Waterford during different times of the year.

The highest intensity on record for the five year period is 6.89 ins./day in JULY, 1963. Higher values must, of course, be expected, the longer the records.

The seasonal variation of absolute rainfall intensity (i.e. most in a day) and the average absolute intensity for the five year period is shown in Fig. 17. There are two maxima for both, the higher maxima occurring in JULY (6.89 ins./day, and 2.42 ins./day respectively)

* For more information on rainfall intensity that is possible over the whole Island refer to a paper by Skeete (1934) in Bibliography.

TABLE 18 NUMBER OF RAINDAYS AND AVERAGE RAINFALL INTENSITY WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			16	18	20	12	19	19	22	24	21	16	
1960	21	11	17	11	14	18	27	23	15	23	10	17	207
1961	24	21	12	15	14	20	24	27	15	19	17	17	225
1962	28	18	09	11	09	23	24	22	22	19	14	14	213
1963	22	19	15	11	17	21	27	19	23	15	20	18	227
1964	10	11											
AVR.	24	17	14	13	15	19	24	22	19	20	16	16	219

Average Intensity (ins./rain day)

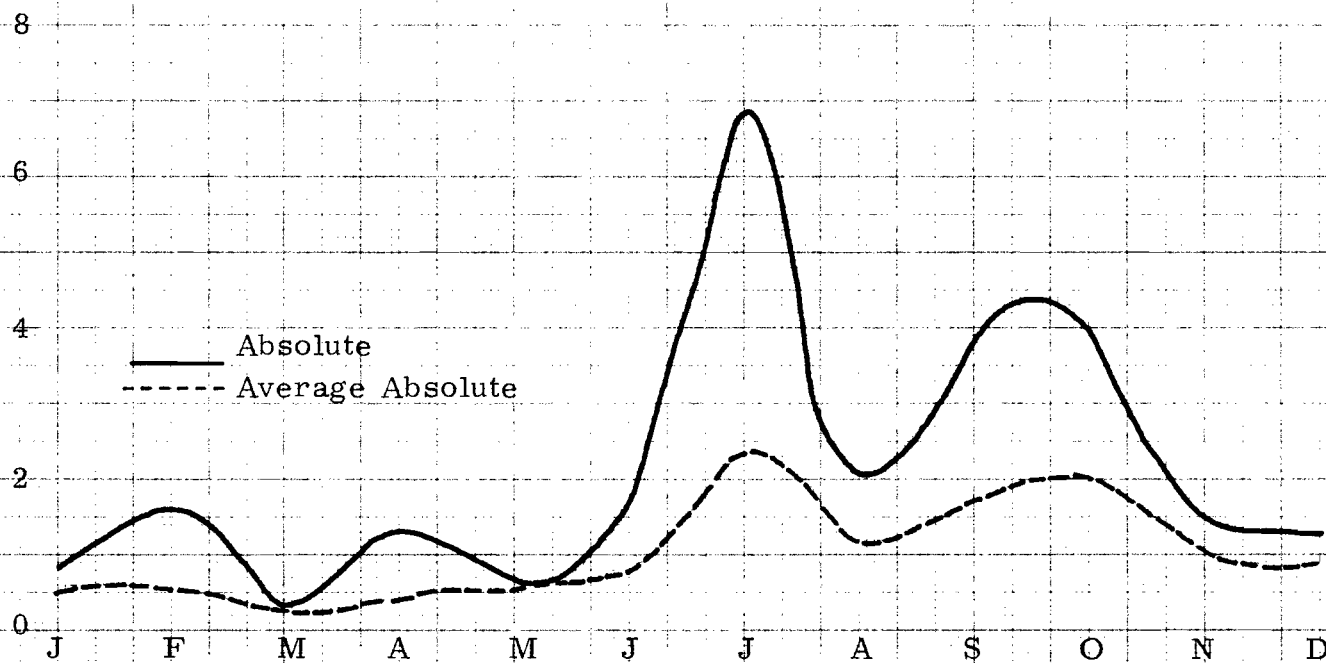
0.10 0.08 0.10 0.10 0.09 0.20 0.31 0.19 0.32 0.31 0.23 0.20

FIG. 17

ABSOLUTE RAINFALL INTENSITY (INS./DAY) WATERFORD BARBADOS

60

(March 1959 - February 1964)



and the lower maximum occurring in the middle of SEPTEMBER (4.5 ins./day and 2.1 ins./day respectively). The seasonal pattern for both absolute and average absolute correspond with the seasonal patterns for monthly rainfall totals and the number of rain days. Figures for absolute rainfall intensity for each month and average absolute intensity are given in Table 19.

The Stability of Annual Average Rainfall

A similar procedure was adopted to determine the length of records necessary to establish a stable average rainfall as was done for temperature (page 42). From the map of relative variability on page 76 it is seen that Waterford is in a region where the relative variability is about 18%. This is high compared with that of temperature (<1%), and suggests that five years records of rainfall is too short to establish a long term average.

Rainfall records for Seawell Airport, covering a period of twenty-two years (1942-1963) were chosen to illustrate the variable character of rainfall regime at Waterford. First, a look was taken at the variation of the five year annual average rainfall covering different periods.

	PERIOD	ANNUAL AVERAGE (ins.)
1.	1942-1946	45.68
2.	1947-1951	53.47
3.	1952-1956	52.60
4.	1957-1961	42.87

TABLE 19 ABSOLUTE RAINFALL INTENSITY (INS./ RAINY DAY) WATERFORD

(Most Rainfall in a Day)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			0.30	1.36	0.75	0.40	0.41	0.39	1.65	4.07	1.02	0.61	4.07
1960	0.94	1.56	0.35	0.47	0.46	0.70	2.14	2.10	0.88	1.30	0.40	1.19	2.14
1961	0.43	0.22	0.21	0.22	0.44	0.32	1.56	0.93	1.03	1.51	1.50	1.20	1.56
1962	0.97	0.20	0.22	0.09	0.60	1.54	1.11	1.28	1.25	1.78	0.78	1.28	1.78
1963	0.60	0.23	0.32	0.09	0.35	1.37	6.89	1.23	3.95	1.48	1.49	0.43	6.89
1964	0.27	0.33											
5 YR. AVR.	0.64	0.51	0.28	0.45	0.52	0.87	2.42	1.19	1.75	2.03	1.04	0.94	1.05
ABS. (March, 1959 - February, 1964)													
	0.97	1.56	0.35	1.36	0.75	1.54	6.89	2.10	3.95	4.07	1.50	1.28	6.89

There is an increase of 18% of the annual average rainfall of the second period over the average of the first period. There is a decrease of only 2% of the average of the third period over the average of the second period, while there is as much as 20% decrease of the average of the fourth period over that of the third period. This is sufficient to show the unstable nature of annual averages of rainfall at Seawell Airport and, therefore, at Waterford. To have an idea of how many years is required to produce a sufficiently stable average, the annual average rainfall for five years, 10 years, 15 years, 20 years and 22 years were calculated for Seawell Airport.

NO. OF YEARS	ANNUAL AVERAGE (ins.)
5	45.68
10	49.58
15	50.59
20	48.66
22	48.59

It appears that averages for twenty years and over may produce a reasonable stability. This is again taken to apply to Waterford also.

In the absence of long records for Waterford we can, however, make use of the method of reduction^{*} (the ratio method in the case of rainfall; Conrad and Pollak, 1962) to work out the annual average rainfall for twenty-two year period for Waterford, given the twenty-two years data for Seawell. This will result in an improvement on the five year mean for climatological purposes. But it must be shown first, whether the method of reduction can be applied with justification in this case.

^{*} Refer to Appendix 3

This will involve showing (i) that the two data series are relatively homogeneous, and (ii) that the quasi-constancy of the ratios of the two rainfall data series is within practical limits (Conrad and Pollak, 1962). Because the data series at Waterford are so short that one is unable to make such tests, the data for Codrington Hill, covering the same period as Seawell Airport data (1942-1960) were used. This is not unreasonable because Codrington Hill and Seawell Airport are in the same climatic region, about 1-1/2 miles apart, and differ in elevation by about 200 ft.

First the relative homogeneity of the two data series was tested. Abbe's criterion (Conrad and Pollak, 1962) was used in testing the homogeneity of the two data series. The criterion is as follows:

$$1 - 1/\sqrt{n} \leq 2A/B \leq 1 + 1/\sqrt{n} \text{ for relative homogeneity}$$

$$\text{where } A = \sum_{i=1}^{i=n} (d_i)^2$$

$$B = \sum_{i=1}^{i=n} (d_i - d_{i+1})^2$$

$$d_i = (\overline{C/S}) - (C/S)_i$$

$(C/S)_i$ is the ratio of the average rainfall at Codrington Hill, C, and Seawell Airport, S,

$(\overline{C/S})$ is the mean of the ratios,

Since the data series is for 19 years, the criterion reduces to

$$0.77 \leq 2A/B \leq 1.23$$

It turned out that $2A/B = 0.96$ for Seawell and Codrington, which lie within the limits. It is therefore probable that the two series are relatively homogeneous.

Another criterion, that of Helmert (Conrad and Pollock, 1962), was applied as a check. His criterion was applied to the same series, d , as was used in the previous test. His criterion is as follows:

$$-\sqrt{n-1} \leq S - C \leq +\sqrt{n-1} \quad \text{for relative homogeneity}$$

where n is the no. of the elements of the series, d ,

S is the no. of sequences* in the series

C is the no. of changes* in the series.

Since $n = 19$, the criterion reduces to,

$$-4.24 \leq S - C \leq +4.24$$

S and C were found to be 7 and 11 respectively for the two stations, so that $S - C = -4$, which lies within the required limits. The two criteria agree with one another, and therefore it is highly probable that the two data series are relatively homogeneous.

Though the series may be homogeneous, there exists a limit beyond which the method of reduction is not permissible.

In general $V_r(C/S) = k V_r(C, S)$

where $V_r(C, S)$ is the relative variability of rainfall at

Codrington Hill or Seawell Airport

$V_r(C/S)$ is the relative variability of their ratios.

k is a constant

* See Appendix 2.

In theory reduction is permissible when $k \leq 1$, but in practice the upper limit may be lower than 1. Conrad has found empirically that $k \leq 0.67$ is a practical limit. In the case under examination k was found to be 0.44.

It may be concluded that the method of reduction can be applied to Waterford rainfall records with respect to Seawell Airport with reasonable accuracy. Below is given figures of the actual five year average and the reduced twenty-two year averages.

J	F	M	A	M	J	J	A	S	O	N	D	Annual
2.35	1.58	1.37	1.30	1.38	3.88	7.37	4.16	6.11	6.21	3.62	3.16	42.29
2.31	2.08	1.50	2.18	2.11	4.41	6.00	5.71	6.76	6.60	6.51	3.52	49.69

The reduction resulted in a substantial increase of about 7 ins. (17%) over the five year annual average.

It can be seen that the above results greatly modify the seasonal variation of rainfall of Waterford described on page 55.

Distribution in the dry season is not changed significantly. Although there are still two maxima rainfall in July and in September, the two peaks are not pronounced. There is rather a general broad maximum from July to November with a slight minimum in August. Also the maximum in September (6.76 ins.) is higher than the maximum in July (6.00 ins.). The rainy season is June to November, and the dry season, December to May. About 72% of the annual average rainfall falls within the rainy season.

The above seasonal distribution of rainfall for Waterford is in agreement with the rainfall regimes at stations around it, like Codrington and Belle Factory, and is therefore to be preferred in climatological work.

Pluviometric Coefficient

The pluviometric coefficient is a good way of presenting the annual course of rainfall, especially when comparison is being made of the annual course at different places. It is defined as,

$$c = 12p_i / p_m$$

where c is the coefficient

p_i is the individual monthly average adjusted
for equal length in a month

p_m is the annual average.

Fig. 18 shows the annual course for both the actual annual rainfall average and the reduced rainfall average.

Cumulative Monthly Rainfall

This is another useful method of showing the annual course of rainfall. Cumulative averages are determined for each month by summing up all the monthly averages from January up to, and including the particular month, and then expressing each cumulative total as a percentage of the annual average. This method is analogous to the method of relative temperatures. Fig. 19 shows the cumulative curve for Waterford. The

FIG. 18

PLUVIOMETRIC COEFFICIENT WATERFORD BARBADOS

68

(March 1959 - February 1964)

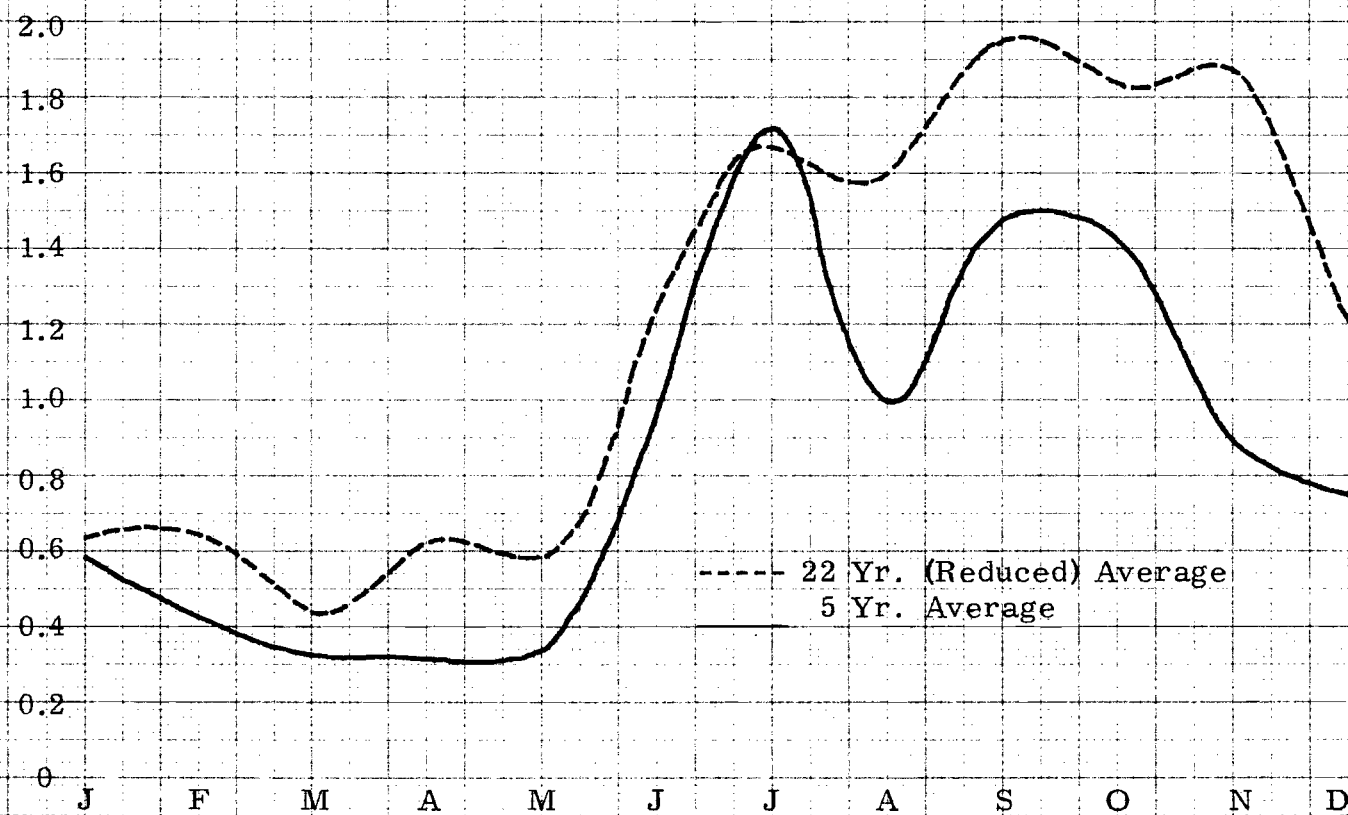
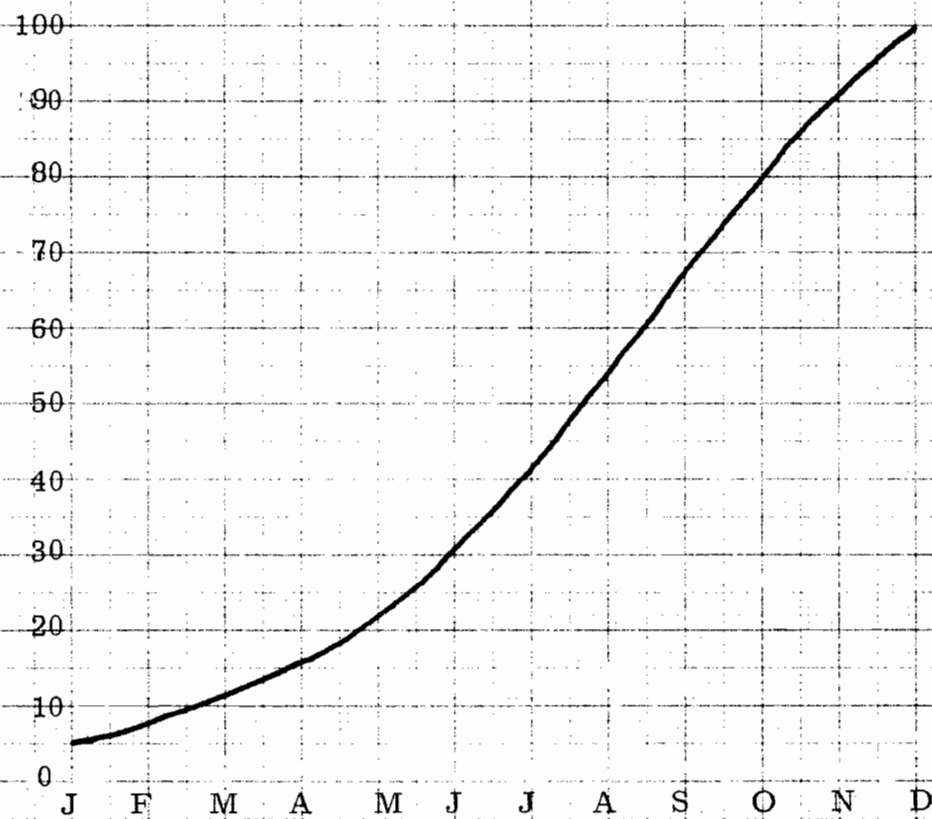


FIG. 19

CUMULATIVE MONTHLY RAINFALL (%)
WATERFORD BARBADOS
(1942 - 1963)

69



rainy season is clearly seen by the steepness of the curve from June to November. Apart from showing the annual course of rainfall which is useful for comparison purposes, the cumulative curve is also useful in determining the percentage of annual amounts that fall within specified periods of the year.

Frequency Distribution of Daily Amounts of Rainfall

In addition to average number of raindays and average rainfall intensity, a knowledge of the frequency of daily amounts is an invaluable climatological information. Quite apart from its usefulness in applied climatology, it may also help towards an understanding of the causes of rainfall regime in a place.

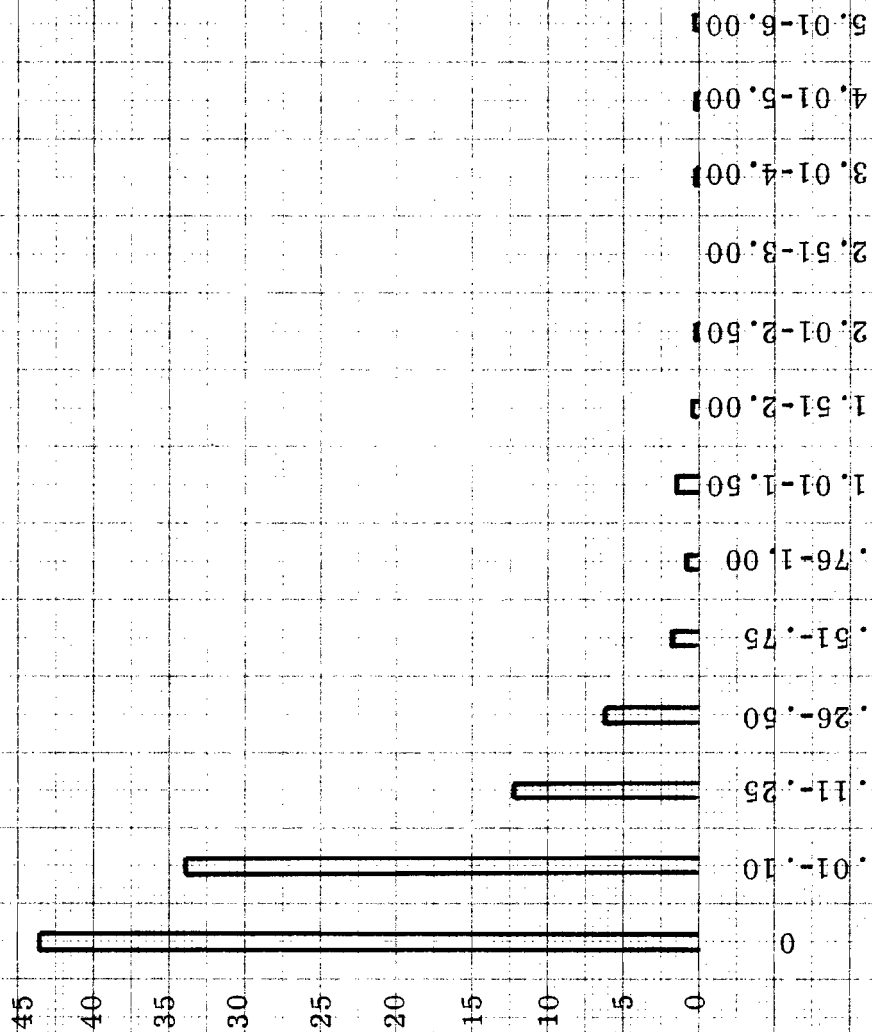
Fig. 20 shows the percentage frequency distribution of daily amounts of rainfall for the five year period. Notice its striking feature, namely, that the maximum frequency occurs at no rain or unmeasurable amounts. In fact, 77% of all days had rainfall amounts not exceeding 0.10 in. Another striking feature is that the frequency falls off very rapidly with increasing rainfall amounts; only 2% of all days had rainfall amounts greater than 1.00 in.

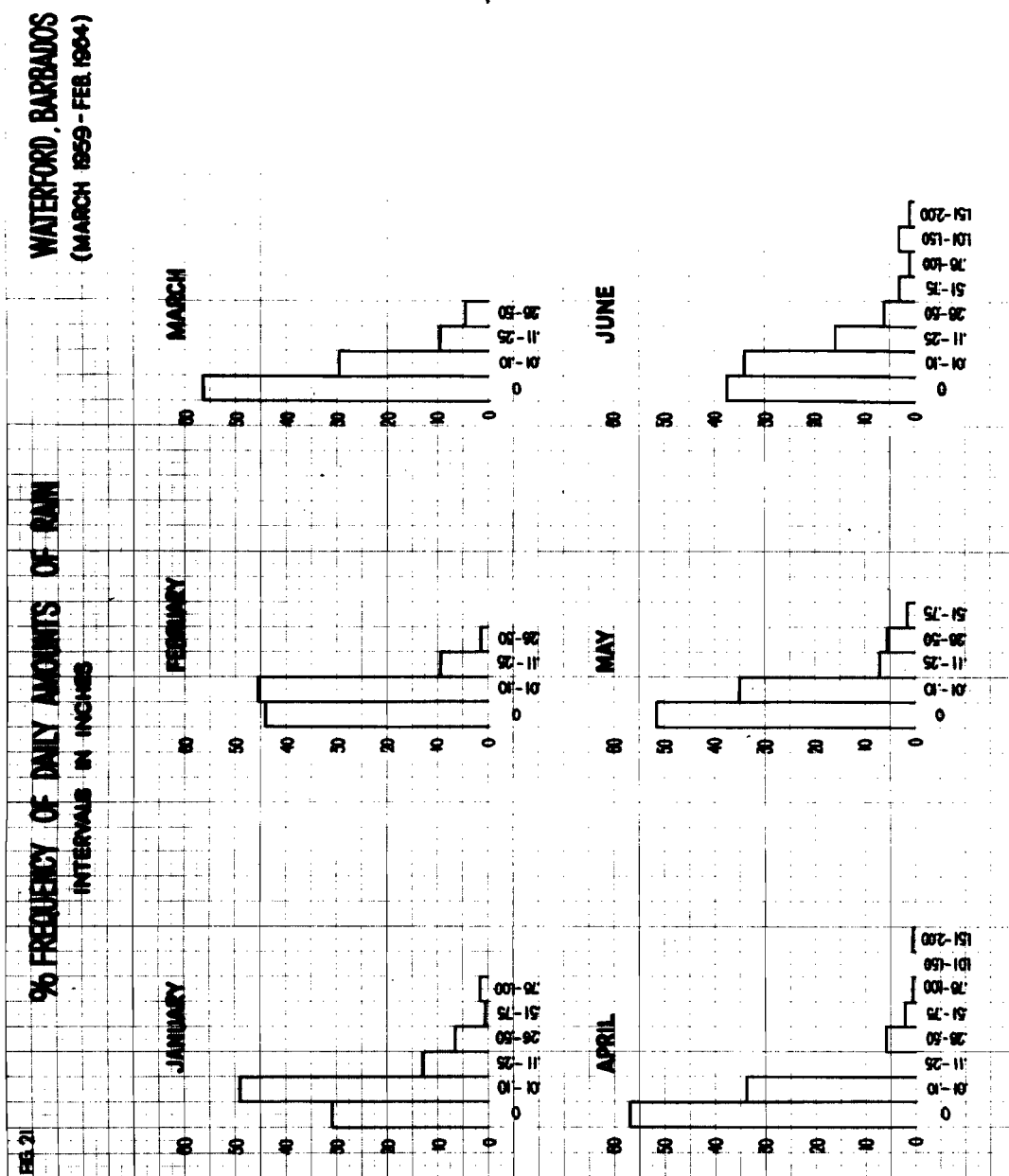
Fig. 21 gives the frequency distribution for the individual months. There are noticeable differences in the monthly distributions, e.g. March-May, July, November and December have a pronounced maximum at no rain or unmeasurable amounts, while January has a pronounced maximum

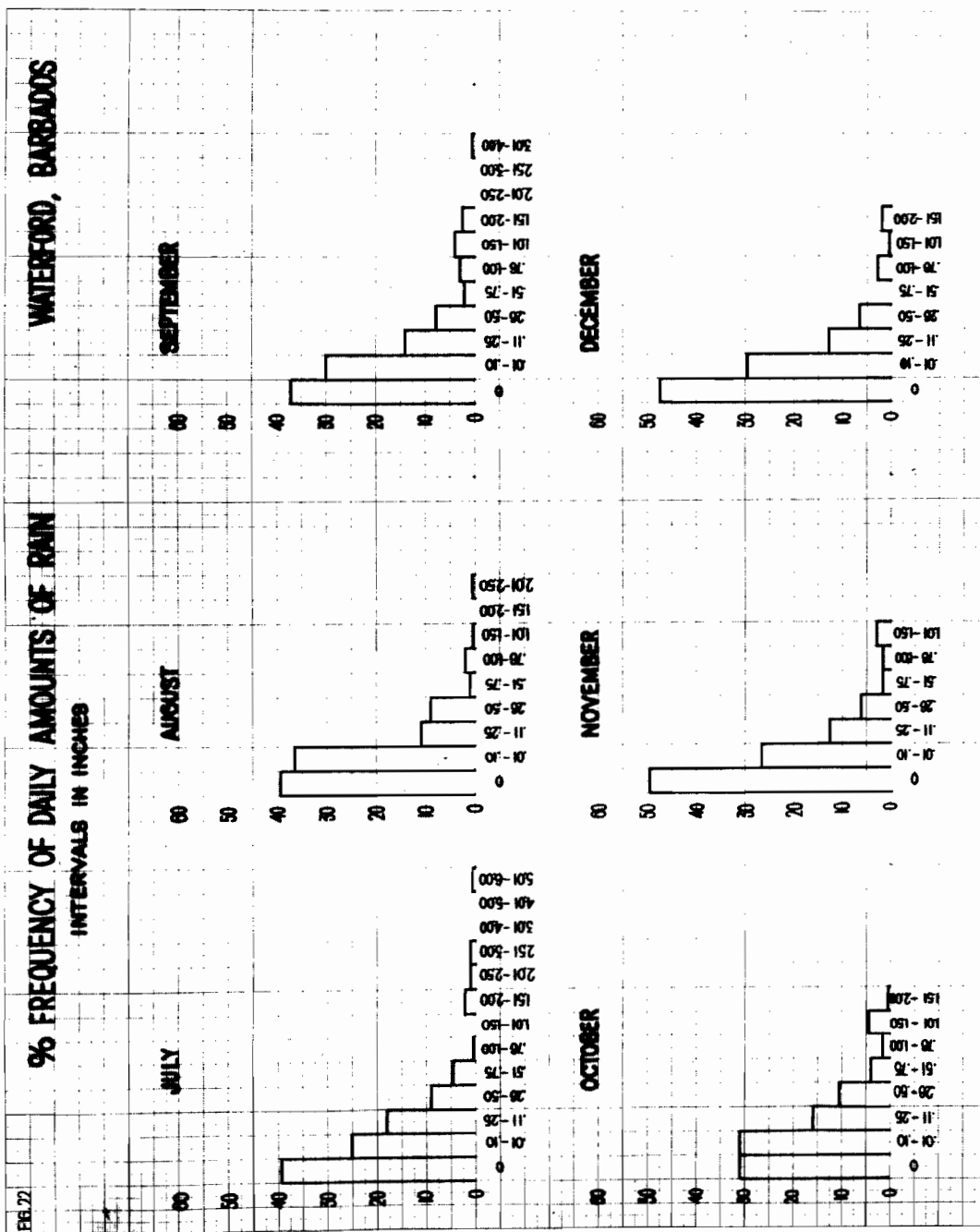
(1000 ft/min)

FIG. 20 % FREQUENCY OF DAILY AMOUNTS OF RAIN WATERFORD BARBADOS 71

(March 1959 - February 1964)







at 0.01-0.10 in. interval. Also notice that all daily amounts of rainfall are confined more or less to amounts not exceeding 0.5 in. from January to May, but spread out over greater amounts from June to December. Table 20 gives the figures for the percentage frequency of daily rainfall amounts.

Rainfall Variability

In attempting to establish a long term average of rainfall and temperature, it was found that the variability of the element is a good indicator of the length of records needed (pages 42,61). Apart from this, rainfall variability is important in many respects, e.g. in geophysical, meteorological, agricultural and hydrological problems. Conrad writes, "From the geophysical, meteorological and climatological standpoints, such variations of precipitation are of great interest. The possibility of years with floods, with abundant crops, and of years with famine at the same place indicates great variability, the explanation of which is a problem for the above sciences." (Conrad, 1941b)

The same rainfall data used by Rouse to prepare a rainfall map of Barbados have been utilized to calculate rainfall variability for fifty-two stations in Barbados. The measure of variability used is the relative variability which, in Conrad's opinion, appears to be the best measure.

Fig. 23 shows a map of rainfall variability for Barbados. Variability over the Island is moderate. It does not exceed 25% in any part

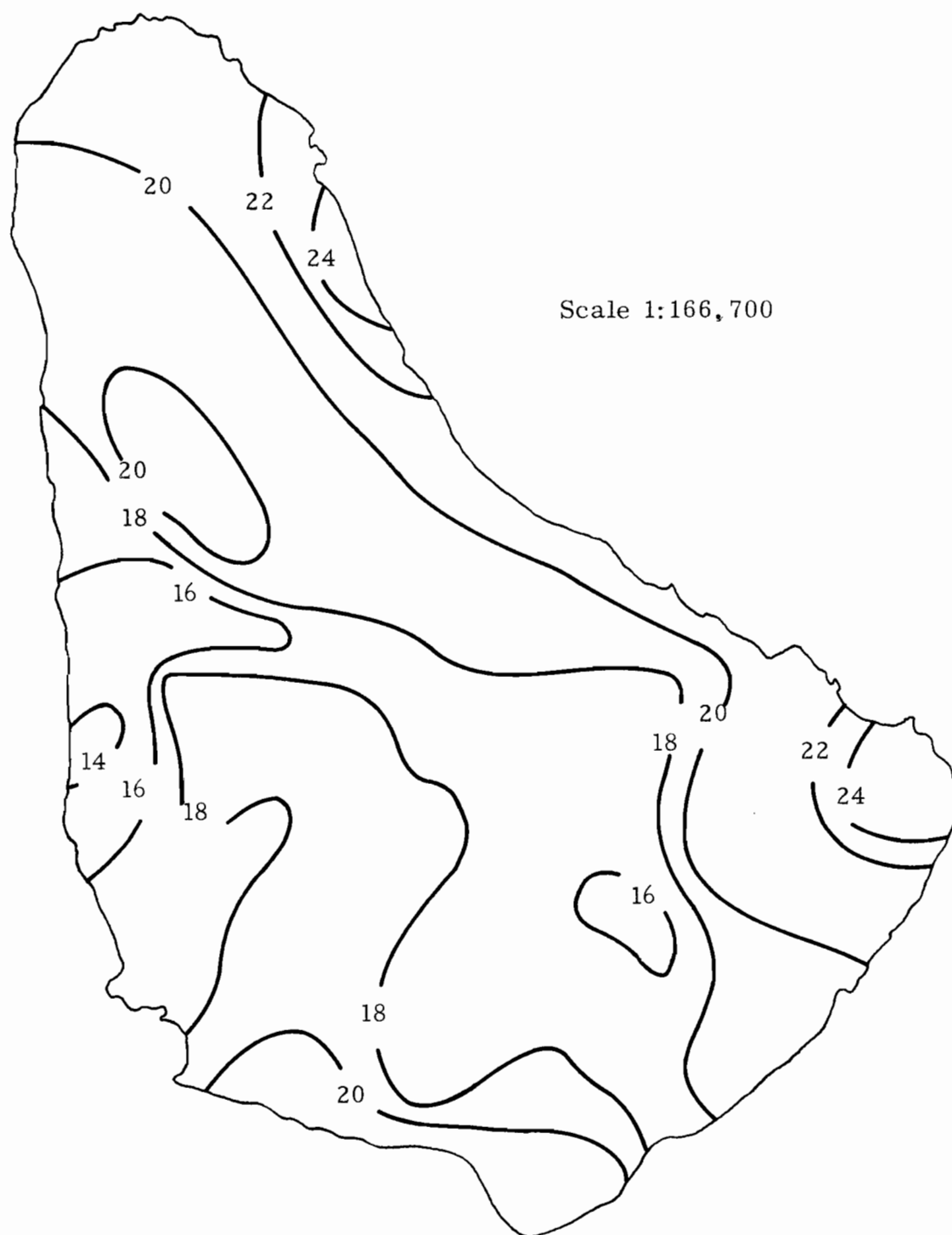
TABLE 20 % FREQUENCY OF DAILY AMOUNTS OF RAINFALL (INS.) WATERFORD BARBADOS

(March, 1959 - February, 1964)

MONTH		.01-	.11-	.26-	.51-	.76-	1.01	1.51	2.01	2.51	3.01	4.01	5.01
	0	.10	.25	.50	.75	1.00	1.50	2.00	2.50	3.00	4.00	5.00	6.00
January	31.0	47.8	12.9	6.4	0.6	1.3							
February	43.7	45.7	9.2	1.4									
March	56.1	29.7	9.7	4.5									
April	56.6	34.0	6.0	2.0	0.7		0.7						
May	51.5	34.9	7.1	5.2	1.3								
June	37.2	34.0	16.0	6.0	2.7	0.7	2.7	0.7					
July	39.5	25.2	18.1	9.0	4.5	0.6	1.9	0.6	0.6				0.6
August	39.5	36.2	10.9	9.0	1.3	1.9	0.6		0.6				
September	37.3	30.0	14.0	8.0	2.0	2.7	3.3	2.0		0.7			
October	31.1	31.0	16.1	10.3	3.9	1.9	4.5	0.6				0.6	
November	49.4	26.6	12.7	6.0	1.3	1.3	2.7						
December	47.2	28.4	12.9	6.4	2.6	0.6	1.9						
Annual	43.5	33.6	12.1	6.2	1.7	0.9	1.5	0.3	0.1		.05	.05	.05

FIG. 23

RAINFALL VARIABILITY (%)
BARBADOS
(1933 - 1957)



values occur over the western coast. Variability of 20% and above occurs over the greater part of the parishes of St. Lucy and St. Philip, along the coastal strips of the parishes of St. Andrew, St. Joseph, St. John and Christ Church, and over a small area to the lee of the hills and covering parts of St. Peter, St. James, St. Andrew and St. Thomas. Values of 16% and below occur over restricted areas over the west coast, covering more than half of St. James, and a little part of St. Thomas, and also a small area to the northwestern corner of St. Philip. The highest variability of 24.1% occurs at River in the parish of St. Philip, and the lowest of 13.8% occurs at Holders in St. James.

Conrad has made a world-wide study of precipitation variability from precipitation data of 360 stations from various latitudinal zones. He obtained an empirical formula which best fits the data. The formula is as follows:

$$v_r = 3600/(\bar{p} + 60) + 13$$

where $\bar{p}$ is the annual average precipitation, an independent variable, in millimeters

v_r is the relative variability, a dependable variable, in percentage

Because the values of v_r and $\bar{p}$ were derived from observations over the whole earth, Conrad regards the above equation as a "normal relation" between the two variables. He also regards their curve as a "standard curve" (Conrad, 1941b).

Because relative variability is shown to be a function of annual average precipitation, values of v_r at different places are not directly comparable with one another. Moreover, no new information may be obtained from a map of relative variability which cannot be obtained from an isohyetal map, especially in areas of low precipitation. A way out of this difficulty is to present rainfall variability in the form of isanormals*. This is done by taking the differences between the actual relative variability of a place and its calculated value from the normal equation. The differences above normal values are termed "positive anomalies," while those below normal values are termed "negative anomalies." Isanormal map is then drawn, which is now free of any dependence of v_r on $\bar{p}$. Areas of positive or negative deviations must therefore be explained "geophysically and not statistically." (Conrad, 1941b)

According to Conrad, v_r becomes independent of $\bar{p}$ when $\bar{p}$ is greater than 28 ins. For a more accurate work v_r becomes practically independent of $\bar{p}$ when $\bar{p}$ is 59.1 ins. and above. Out of fifty-two stations used in Barbados, 58% had $\bar{p}$ less than 59.1 ins., the lowest $\bar{p}$ being 46.4 ins. A scatter diagram was therefore drawn between v_r and $\bar{p}$ to see if there was any dependence between the two variables. The diagram shown in Fig. 24 does not reveal any obvious correlation. Presentation of the relative variability map in Fig. 23 is therefore an additional important climatological information which the isohyetal map (Fig. 25) does not reveal. In fact, the features of the two maps are different, e.g., areas of lowest

* Refer to Appendix 2.

FIG. 24 SCATTER DIAGRAM OF RELATIVE VARIABILITY
AND ANNUAL AVERAGE RAINFALL BARBADOS

(1933 - 1957)

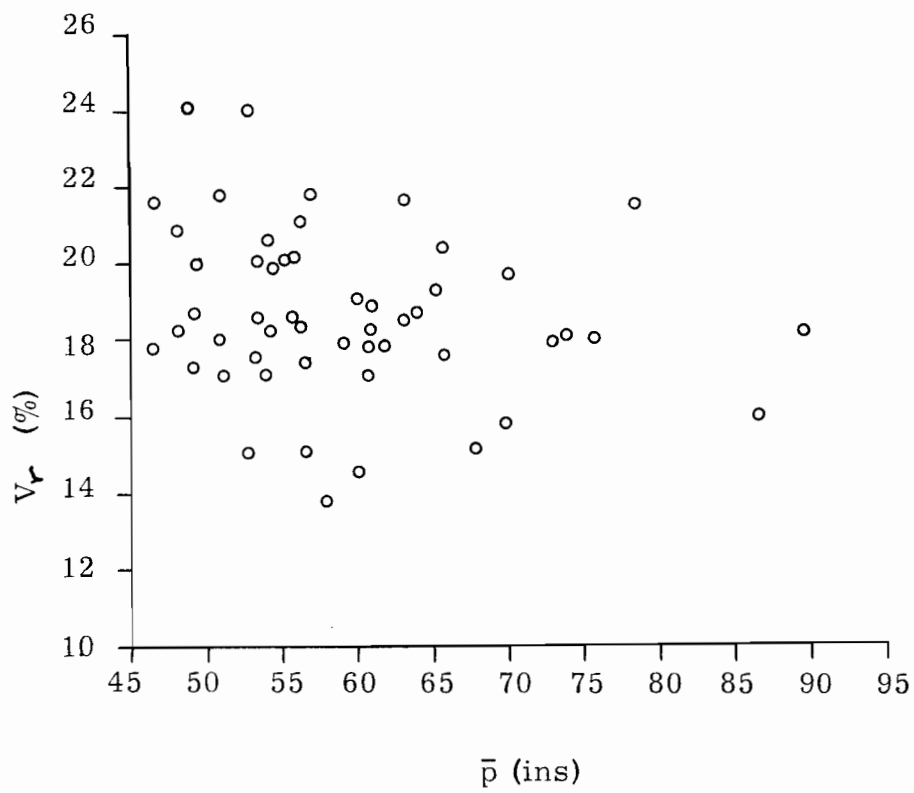
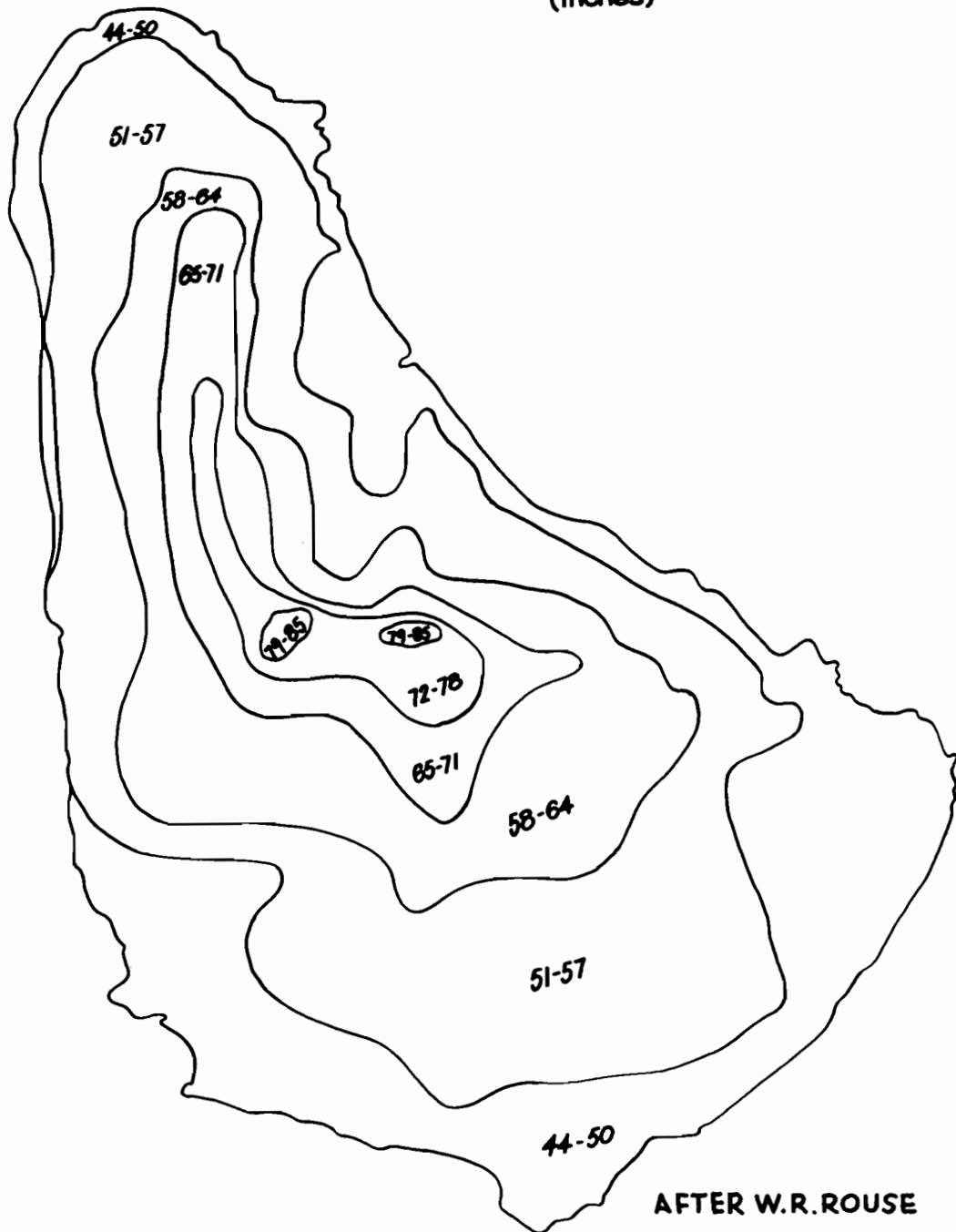


FIG. 25

BARBADOS
MEAN ANNUAL RAINFALL
(Inches)



variability are not the areas of highest rainfall.

In spite of the above conclusions an isanormal map of rainfall variability is also presented for three reasons. (1) It may be useful when comparing rainfall variability of Barbados with that of other areas where annual average rainfall is below 28 ins. (2) Areas of positive and negative anomalies may yield useful information on the nature of precipitation regime over various parts of the Island as well as being of practical use to various users of climatological information like the agriculturist and hydrologist. (3) According to Conrad, the principal importance of the anomaly of variability is in dynamic climatology. (Conrad, 1941b)

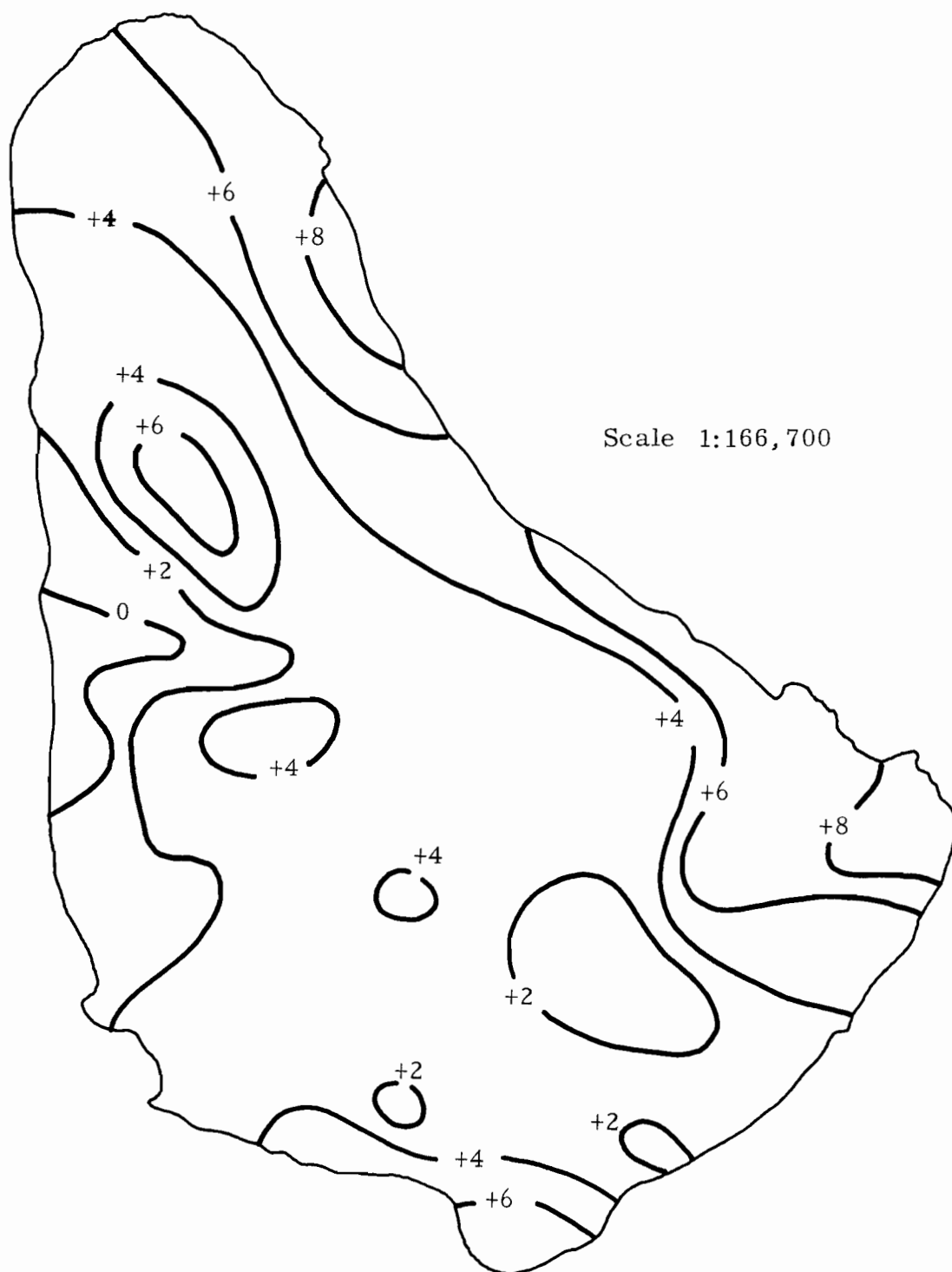
Fig. 26 shows the isanormal map of rainfall variability in Barbados. Practically the whole Island has positive anomalies and the areas of highest positive anomalies coincide with the areas of highest variability. Negative anomalies are confined to a very small area coinciding with the area of the lowest variability. Below is a frequency table of the anomalies from the fifty-two stations.

% Frequency of Anomaly of Variability of Rainfall (%)

0	0. -2.0	2.1-4.0	4.1-6.0	6.1-8.0	8.0
6	14	46	21	9	4

It is seen that only 6% of the cases had negative anomaly, the highest being 1.3. The rest of the cases, 94% , all had positive anomalies of which 46% lie within the interval 2.1-4.0. The highest positive anomaly of 8.7 occurs in Morgan Lewis in St. Andrew.

RAINFALL
FIG. 26 ISANORMALS OF RELATIVE VARIABILITY (%)
BARBADOS
(1933 - 1957)



The positive anomalies are far more frequent and more intense than the negative anomalies. This indicates that on the whole, rainfall regime in Barbados is more variable than is expected, except over the small area in the parish of St. James on the west coast, where rainfall regime is steadier than expected.

Figures for annual average rainfall, rainfall variability and anomaly of rainfall variability are given in Table 21.

III SURFACE WIND

The surface wind data for Waterford is only three years for the speed and 2 years for the direction. However, the analysis of the data still gives some useful information.

Prevailing Surface Wind Direction

(a) 0900 hrs : The surface wind direction is clearly East. During the whole year the wind blows from the East 45% of the time. It blows from ENE through E to ESE most of the time (89%). Considering the individual months, the prevailing wind direction is E throughout the year, except in JULY and AUGUST, when the prevailing wind direction becomes ESE. The easterly wind is most regular in the months of DECEMBER (69.5%) JANUARY (69.3%) and FEBRUARY (68.0%).

(b) 1600 hrs : The prevailing wind direction is East, with annual frequency of 49%. It blows from ENE through E to ESE most of the time (86%). The prevailing wind direction is East in all months,

TABLE 21 RAINFALL VARIABILITY AND ANOMALY OF VARIABILITY
 BARBADOS (1933 - 1957)

STATION	$\bar{p}$ (ins.)	V_r (normal) %	V_r (actual) %	V_r anomaly %
St. Lucy				
Hope	53.86	15.3	21.6	6.3
Husband's	54.32	15.2	19.9	4.7
Pickerings	54.88	15.2	20.1	4.9
St. Andrew				
Morgan Lewis	52.32	15.3	24.0	8.7
Turner's Hall	63.97	15.0	18.7	3.7
Cleland Factory	60.75	15.0	18.8	3.8
St. Joseph				
Bissex Hill House	65.62	15.0	20.4	5.4
St. John				
Colleton Factory	61.67	15.0	17.8	2.8
Clifton Hall	63.16	15.0	18.5	3.5
Claybury	75.43	15.0	18.1	3.1
Newcastle	55.21	15.2	21.2	6.0
Kendal	65.50	15.0	17.6	2.6
St. Philip				
Mangrove	50.63	15.4	18.0	2.6
Congo Road	49.18	15.5	20.8	5.3
River	48.78	15.5	24.1	8.6
Ruby	53.30	15.3	21.0	5.7

$\bar{p}$ = annual average rainfall in ins.

$$V_r(\text{normal}) = \frac{141.7}{\bar{p} + 2.36} + 13$$

$$V_r(\text{actual}) = \sum_{i=1}^{i=n} |p_i - \bar{p}| / n$$

TABLE 21 (Continued)

STATION	$\bar{p}$ (ins.)	V_r (normal) %	V_r (actual) %	V_r anomaly %
St. Philip (Cont'd)				
Carrington	56.32	15.1	15.7	0.6
Govt. Industrial				
School	50.93	15.4	21.8	6.4
Mount Pleasant	56.02	15.1	21.1	6.0
Christ Church				
Kingsland Factory	53.71	15.3	17.1	1.8
Ealing Grove	46.31	15.6	21.6	6.0
Seawell Airport	48.93	15.5	17.3	1.8
Graeme Hall	48.00	15.6	20.8	5.2
Balls	49.29	15.5	18.7	3.2
Searles	53.63	15.3	17.7	2.4
Spensers	48.22	15.6	18.2	2.6
St. George				
Hanson	55.23	15.2	18.3	3.1
Bulkeley Factory	59.00	15.0	17.9	2.9
Boarded Hall	56.53	15.1	17.4	2.3
Jordans	60.33	15.0	19.0	4.0
Cottage	73.68	15.0	18.0	3.0
St. Michael				
Lears	60.77	15.0	17.9	2.9
Codrington Hill	51.05	15.4	17.0	1.6
Bell Factory	53.86	15.3	18.2	2.9
Central Police				
Station	46.38	15.6	17.8	2.2
Warrens	52.79	15.3	18.6	3.3
St. Thomas				
Lion Castle	86.63	14.8	15.9	1.1
Vaucluse Factory	65.07	15.0	19.2	4.2
Fisherpond	73.02	15.0	17.9	2.9
Hopewell	70.24	15.0	19.7	4.7

TABLE 21 (Continued)

STATION	$\bar{p}$ (ins.)	V_r (normal) %	V_r (actual) %	V_r anomaly %
St. Thomas (Cont'd)				
District D (Police Station)	67.71	15.0	15.1	0.1
Canefield	89.51	14.7	18.1	3.4
Bennett's	60.92	15.0	18.2	3.2
St. James				
Holdings	57.76	15.1	13.8	1.3
Holetown	59.94	15.0	14.5	0.5
Sandy Lane Factory	52.51	15.3	15.1	0.2
Lancaster	69.82	15.0	15.8	0.8
Ape's Hill	78.26	15.0	21.5	6.5
St. Peter				
Alleyndale	60.51	15.0	17.1	2.1
Heywoods	55.72	15.2	18.4	3.2
Nicholas Abbey	56.80	15.1	21.8	6.7
Mangrove	62.90	15.0	21.6	6.8

except in NOVEMBER when it becomes ENE. The easterly wind is most regular in the months of APRIL (75.1%), DECEMBER (72.5%), FEBRUARY (69.7%) and JANUARY (67.8%).

At both hours of observation, the frequency of winds having a southerly component increases markedly between June and November by more than twice the frequency of such winds during December to April. This clearly marks the rainy season and the dry season.

The figures for the per cent frequency of wind direction at 0900 hrs. and 1600 hrs. are given in Tables 22 and 23.

Figs. 27 and 28 show the wind roses for the surface wind direction for Waterford. They show the annual course of frequency of wind blowing from each of the sixteen compass points. Both roses show clearly the prevailing wind direction to be East. Also they show clearly that almost all wind is confined between NE and SE. At 1600 hrs. winds of small frequency (<1%) also blow from the other directions, while at 0900 hrs. no winds blow from between N and W.

Resultant or Mean Wind*

Though surface wind speed direction was observed twice a day, the wind speed was observed as a 24-hr. - run, so that wind speeds with their associated direction are not available. The resultant of mean wind could therefore not be calculated. However, the resultant wind direction was calculated by using the percentage frequency of surface wind dir-

* Refer to Appendix 2.

TABLE 22 PERCENTAGE SURFACE WIND FREQUENCY (0900) WATERFORD

(May 1961 - April 1963)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
N									1.7				0.1
NNE									1.7	1.6			0.3
NE	6.5	5.4	3.2	6.7	1.6	1.7	1.6	9.7		1.6	5.0	1.6	3.7
ENE	22.6	17.8	33.9	15.0	8.1	18.3	25.8	11.2	10.0	12.9	31.7	16.1	19.5
E	69.3	68.0	46.8	63.3	37.0	36.7	25.8	38.7	35.0	37.0	25.0	69.5	45.2
ESE	1.6	8.9	12.9	15.0	37.0	41.7	35.5	30.7	30.0	35.5	25.0	13.0	23.9
SE			3.2		9.7		8.1	4.8	5.0	1.6	5.0		3.1
SSE							1.6	1.6	6.7	4.8	3.3		1.5
S					3.2	1.7	1.6	3.2	5.0	3.2	3.3		1.8
SSW					1.6					1.6			0.3
SW									3.3		1.7		0.3
WSW					1.6				1.7				0.3
W													
WNW													
NW													
NNW													

TABLE 23

PERCENTAGE SURFACE WIND FREQUENCY (1600) WATERFORD

(May 1961 - April 1963)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
N							4.8	3.2	1.7		1.7		1.0
NNE								1.6		3.2			0.4
NE	8.1	1.8	3.2	1.7		3.3	6.5	4.8	5.0		5.0	1.6	3.4
ENE	21.0	23.2	27.5	15.0	9.7	15.0	16.1	27.5	15.0	6.5	28.3	16.1	18.4
E	67.8	69.7	46.8	75.1	46.7	56.7	37.0	27.5	25.0	37.0	26.7	72.5	49.0
ESE	1.6	3.6	9.7	6.7	32.3	20.0	30.7	25.8	23.3	38.7	20.0	8.1	18.4
SE	1.6		8.1		3.2	5.0	1.6	3.2	10.0	6.5	5.0		3.7
SSE				1.7	1.6		1.6	1.6	6.7		1.7		1.2
S		1.8			3.2		1.6	1.6	5.0	3.2	6.7	1.6	2.1
SSW					1.6				3.3		1.7		0.6
SW								1.6	3.3		3.3		0.7
WSW										1.6			0.1
W			3.2		1.6				1.7	1.6			0.7
WNW			1.6										0.1
NW								1.6					0.1
NNW										1.6			0.1

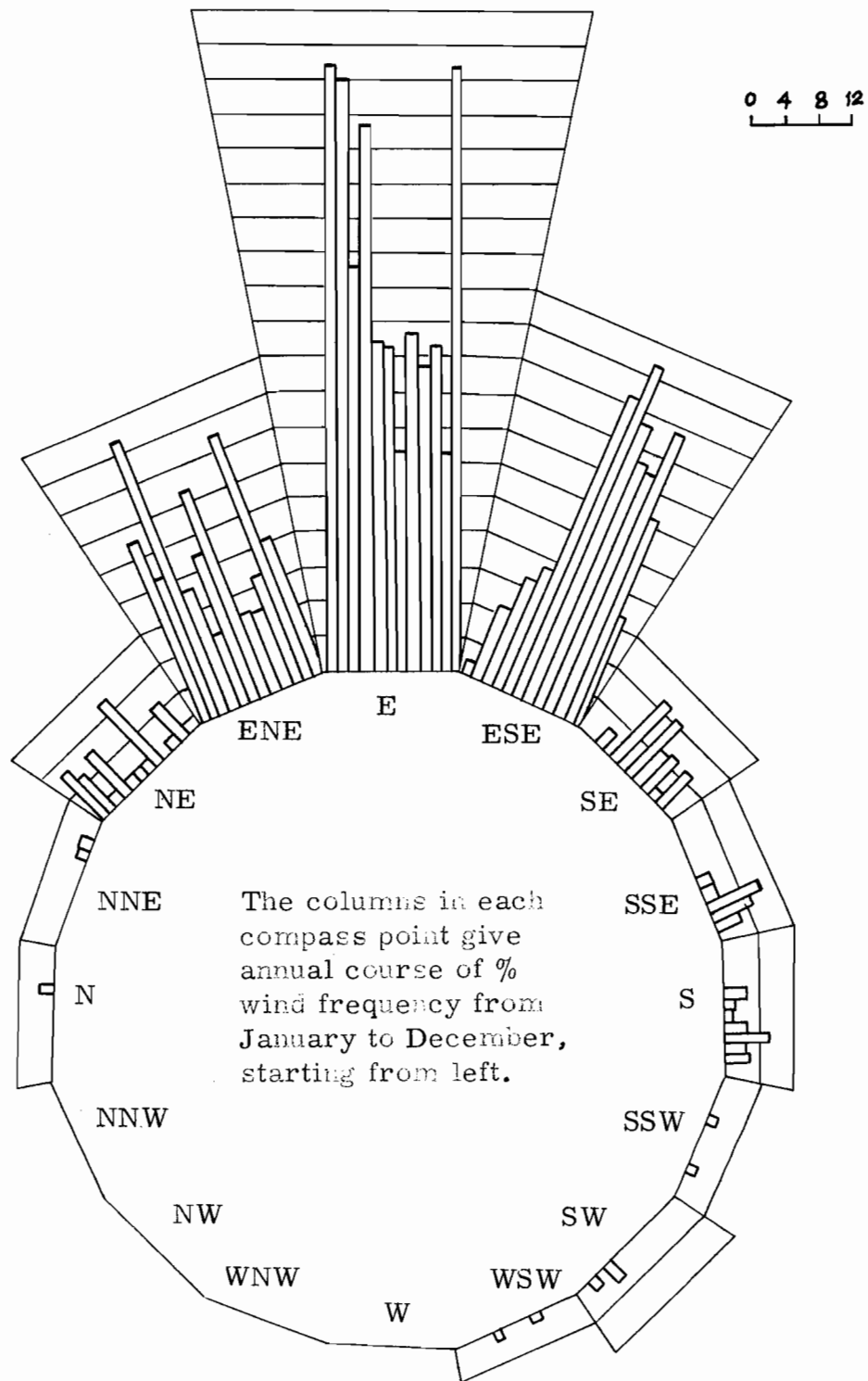


FIG. 27 WIND ROSES FOR WATERFORD, BARBADOS
0900 HRS.

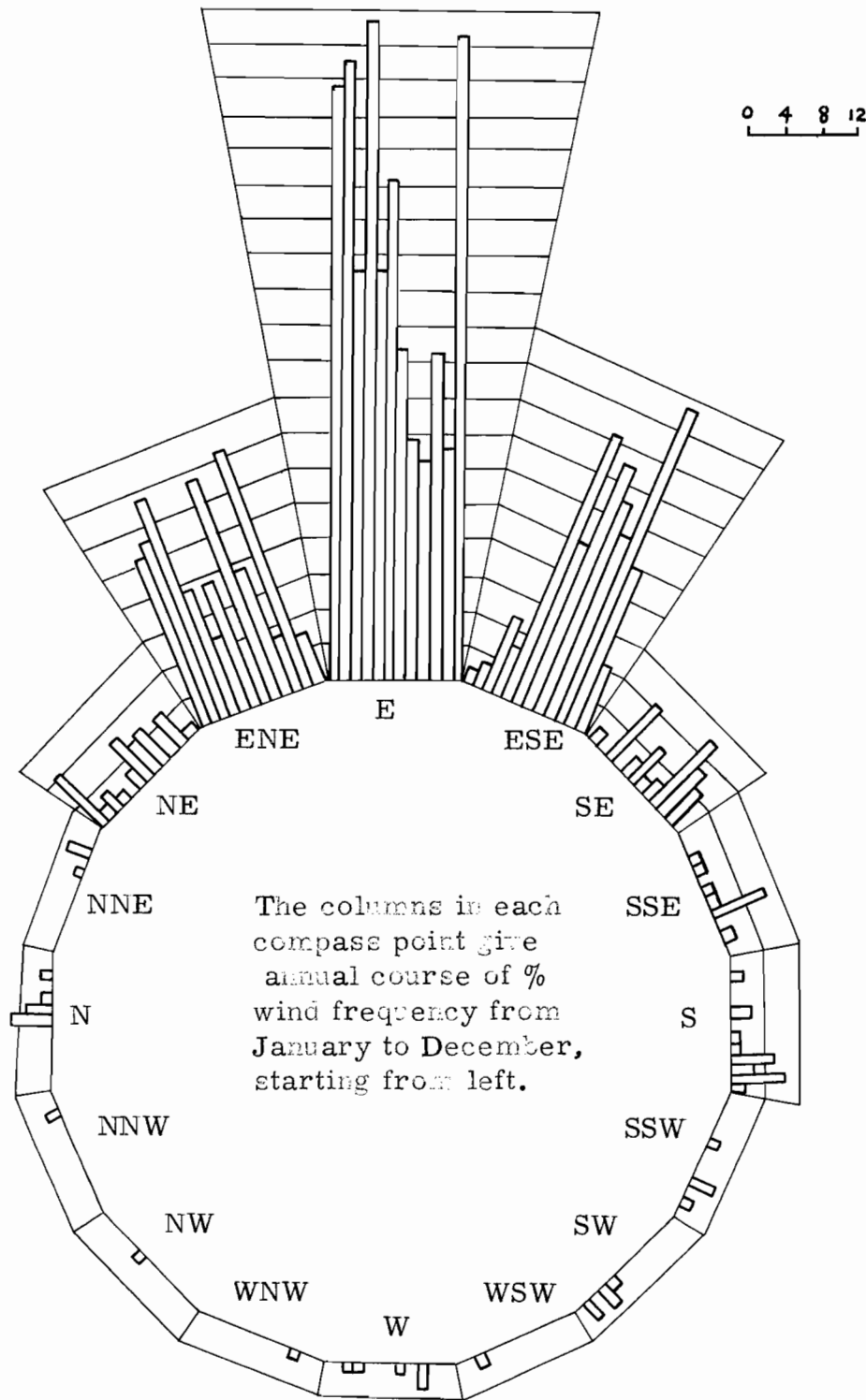


FIG.28 WIND ROSES FOR WATERFORD, BARBADOS
1600 HRS.

ection in Tables 20 and 21. This method assumes that the average wind speed is roughly proportional to the frequency of wind direction, e.g., if the East wind is the most frequent, it is also the strongest. (Conrad and Pollak, 1962) The resultant wind direction was $91^{\circ} 48'$ at 0900 hrs. and $93^{\circ} 06'$ at 1600 hrs., not being more than 4° from the prevailing wind direction. This result emphasizes the steadiness of surface wind in Waterford.

Surface Wind Speed

Surface wind speed is generally low. The annual average daily wind speed is 4.7 mph. The lowest average wind speeds occur in NOVEMBER (2.6 mph.), while the highest occur in JUNE (7.3 mph.). Average winds in MARCH-JULY are about 4 mph. higher than the average winds during the rest of the year. The daily mean wind speed can rise as high as 13 mph. in MAY, and drop as low as 0.8 mph. in NOVEMBER. Figures for monthly means of daily mean wind speed, most speed in a day, and least speed in a day, are given in Table 24. Curves showing their annual course are also shown in Fig. 29.

The cause of the low winds in Waterford may be due to lack of openness of the observing station.* Codrington Agricultural Station which is nearby, and is more open, has daily mean wind speeds about twice as much as those of Waterford. Figures for monthly means of daily mean wind speed, most speed in a day, and least speed in a day, for Codrington are also given in Table 25.

* Refer to Appendix 1.

TABLE 24 MONTHLY MEAN DAILY MEAN WIND SPEED (MLS/HR) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960					5.8	6.1	4.3	3.6		3.4	2.6	3.4	
1961	4.1	4.2	6.4		8.4	8.4	5.6	4.7	2.9	3.2	2.5	3.2	5.1
1962	4.4	4.4	3.4	6.9	6.0	7.4	5.9	4.2	3.4	2.5	2.8	3.4	4.6
1963	4.2	4.2	6.0	5.3	6.9	7.3	5.2	3.3	3.2	2.2	2.7	3.8	4.5
1964	3.7	3.5	7.0	8.1									
4 YR. AVR.	4.1	4.1	5.7	6.8	6.8	7.3	5.3	4.0	3.2	2.8	2.6	3.4	4.7

TABLE 24 (Continued)

DAILY MEAN WIND SPEED, MOST IN A DAY (MLS/HR) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960					8.7	9.9	7.9	8.9	4.0	6.1	5.0	6.4	12.6
1961	6.0	7.1	9.7	11.6	13.0	11.8	10.0	8.6	6.1	5.3	4.0	6.0	13.0
1962	6.9	7.0	6.8	10.8	12.5	10.8	10.0	7.1	6.0	5.3	4.8	10.4	12.5
1963	7.6	7.6	9.8	7.6	10.2	10.0	8.4	6.4	9.1	3.3	4.2	9.2	10.2
1964	6.8	5.8	12.6	12.0									
4 YR. AVR.	7.6	7.6	12.6	12.0	13.0	11.8	10.0	8.9	9.1	6.1	5.0	10.4	13.0

TABLE 24 (Continued)

DAILY MEAN WIND SPEED, LEAST IN A DAY (MLS/HR) WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960					3.3	3.6	2.1	1.3	1.1	1.5	1.4	1.8	1.1
1961	2.9	2.0	3.3	3.6	5.2	3.7	1.8	2.2	1.4	1.7	1.2	1.2	1.2
1962	2.2	1.3	2.0	3.3	2.6	4.3	3.6	2.1	1.3	1.1	0.8	1.3	0.8
1963	1.4	1.8	2.1	2.9	3.8	3.5	1.3	1.5	1.2	1.3	1.6	1.5	1.2
1964	2.1	2.0	3.8	5.2									
4 YR. AVR.	1.4	1.3	2.0	2.9	2.6	3.5	1.3	1.3	1.1	1.1	0.8	1.2	0.8

FIG. 29 DAILY MEAN SURFACE WIND SPEED (MPH) WATERFORD BARBADOS
(May 1961 - April 1963)

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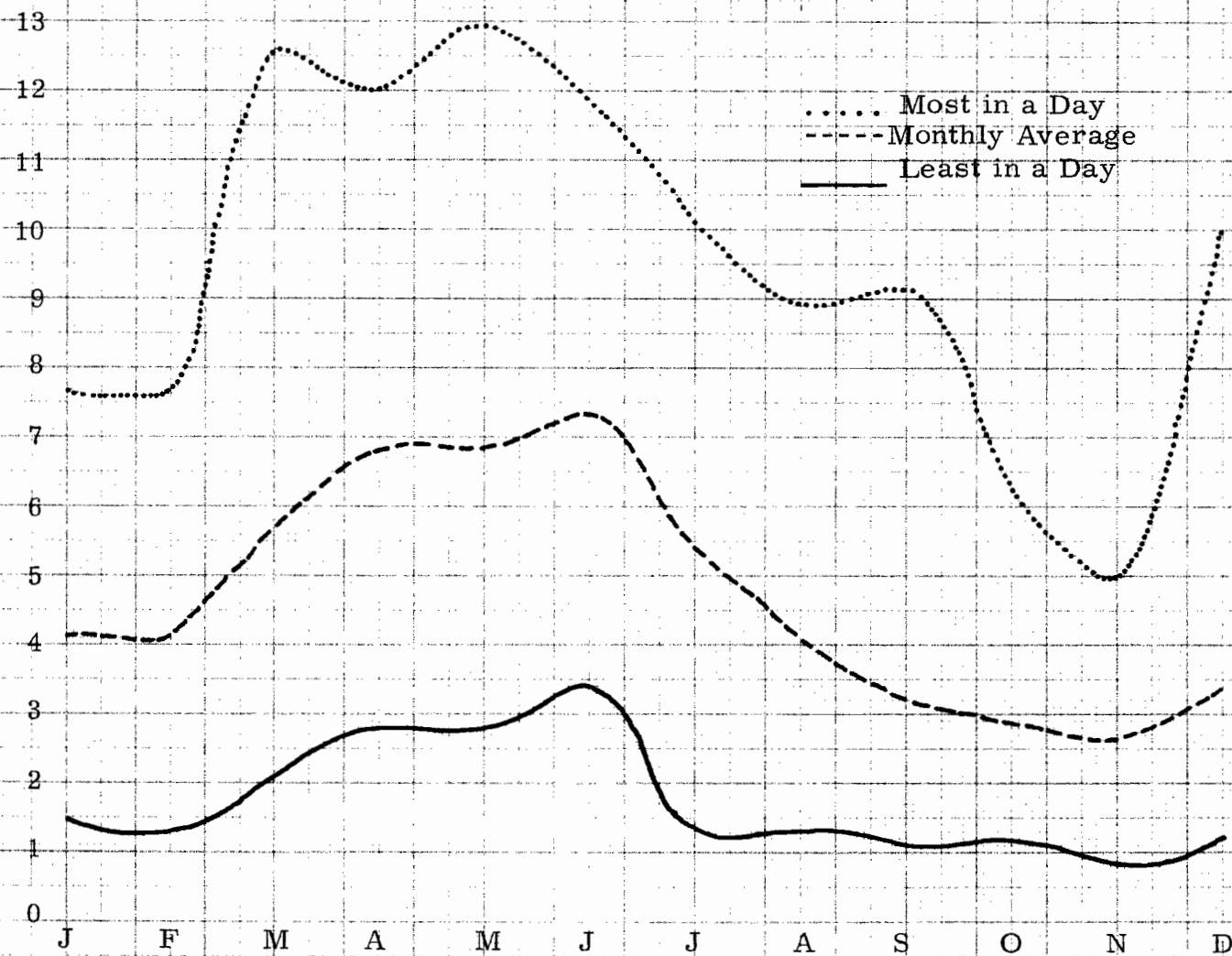


TABLE 25 MONTHLY MEAN DAILY MEAN WIND SPEED (MLS/HR) CODRINGTON

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959	8.9	9.2	9.3	8.6	10.2	12.4	9.8	9.2	6.4	7.8	7.0	4.9	8.7
1960	7.4	7.3	8.9	9.4	9.2	10.4	8.2	8.1	5.3	7.5	6.6	7.4	8.0
1961	9.7	10.3	9.0	9.8	11.2	12.3	9.0	8.1	5.8	6.7	5.4	7.9	8.8
1962	9.8	9.9	7.8	10.3	7.9	10.0	8.7	7.2	6.4	6.0	6.4	7.2	8.1
1963	8.8	9.2	11.6	6.9	10.4	11.0	8.7	6.2	6.0	4.4	6.3	9.2	8.2
5 YR. AVR.	8.9	9.2	9.5	9.0	9.8	11.2	8.9	7.8	6.0	6.5	6.3	7.3	8.4

TABLE 25 (Continued)

DAILY MEAN WIND SPEED, MOST IN A DAY (MLS/HR) CODRINGTON

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959				13.4	14.5	16.4	15.3	16.4	9.3	17.7	10.2	9.7	17.7
1960	11.4	11.3	11.9	12.8	12.7	16.0	11.8	14.8	7.5	11.8	10.6	11.3	16.0
1961	12.9	15.0	12.0	13.2	17.2	17.4	17.8	12.8	11.2	10.2	9.0	11.4	17.8
1962	12.8	14.4	13.5	12.7	14.0	13.3	13.7	11.7	11.0	9.6	9.2	13.2	14.4
1963	13.7	13.1	15.7	10.8	12.6	13.6	13.0	10.3	11.7	6.2	9.1	14.0	15.7
1964	14.5	11.5	15.8										
5 YR. AVR.	14.5	15.0	15.8	13.4	17.2	17.4	17.8	16.4	11.7	17.7	10.6	14.0	17.8

TABLE 25 (Continued)

DAILY MEAN WIND SPEED, LEAST IN A DAY (MLS/HR) CODRINGTON

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959				4.5	4.5	4.7	5.4	3.9	3.2	3.5	3.4	2.3	2.3
1960	4.8	5.0	5.8	6.8	6.8	7.2	4.5	4.9	3.4	4.0	3.2	4.8	3.2
1961	6.8	6.0	5.3	5.8	7.8	5.7	3.1	4.0	2.8	1.9	2.9	3.9	1.9
1962	5.7	3.2	3.3	7.8	3.1	6.7	4.3	3.2	2.7	3.3	3.2	4.1	2.7
1963	5.1	5.3	5.7	4.8	6.4	5.8	3.1	3.2	2.5	2.9	3.7	4.7	2.5
1964	6.2	5.6	5.4	6.8									
5 YR. AVR.	4.8	3.2	3.3	4.5	3.1	4.7	3.1	3.2	2.5	1.9	2.9	2.3	1.9

Wind speeds are expected to be high over the hills. They become still higher and gusty during tropical storms. For more details refer to Skeete (1934, 1951) and Barbados Weather Observatory (1956).

Steadiness of Surface Wind

The measure of steadiness used is the directional wind steadiness.* Fig. 30 shows the annual course of surface wind steadiness at 0900 hrs. and 1600 hrs. It does not fall below 60% at any time of the year. It is over 80% from the middle of November to June. The wind is most persistent in February (97%) and April (97%). From about the middle of July to the beginning of January, and also in March, the steadiness of wind at 0900 hrs. is higher than that at 1600 hrs. From the beginning of April to the middle of July the steadiness at 0900 hrs. becomes lower than that at 1600 hrs.

IV RELATIVE HUMIDITY

Relative Humidity readings are taken twice a day, at 0900 hrs. and 1600 hrs. Annual average relative humidity is 68% at 0900 hrs. and 66% at 1600 hrs. There is very little variation in the annual mean relative humidity. It appears to be the most stable parameter. The relative variability for the annual mean of both 0900 hrs. and 1600 hrs. is less than 0.5%. The five years records are therefore sufficient for climatological purposes.

The seasonal variation of relative humidity is not great. The annual range of relative humidity for both 0900 hrs. and 1600 hrs. is

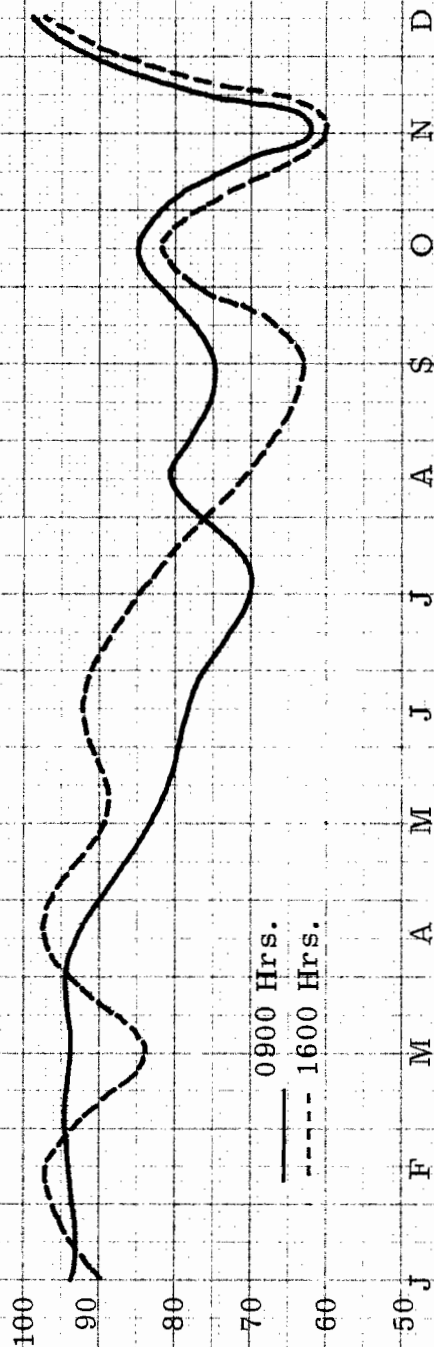
* Refer to Appendix 2.

FIG. 30

WIND STEADINESS (%) WATERFORD BARBADOS

(May 1961 - April 1963)

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12%. The highest relative humidity occurs in OCTOBER at 0900 hrs. and 1600 hrs. with monthly averages of 73% and 72% respectively, while the lowest occurs in APRIL with monthly averages of 61% and 60% at 0900 hrs. and 1600 hrs. respectively.

Figures for monthly means of relative humidity for 0900 hrs. and 1600 hrs. are given in Tables 26 and 27, and graphs showing their seasonal variation are found in Fig. 31.

V SUNSHINE DURATION

Measurements of sunshine duration are made at Codrington Station. The data can, however, be used for Waterford since possible sunshine hours over plains do not vary greatly (Landsberg, 1960).

The annual average sunshine duration per day is 8.7 hrs. There is very little variation of this parameter from year to year. There is also very little seasonal variation, the annual range being only 1.4 hrs. Sunshine duration is as stable as temperature and relative humidity. The five years records therefore appear sufficient for climatological purposes.

Unlike the other parameters it has three maxima and three minima during the year. The graph in Fig. 32 is exaggerated to bring out the seasonal variation, which though small, doubtless has important climatological implications. The maxima occur in JANUARY (9.1 hrs.),

TABLE 26 MONTHLY MEAN RELATIVE HUMIDITY 0900 HRS. (%) WATERFORD BARBADOS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959				65	67	66	69	64	69	75	71	70	
1960	66	66	62	66	63	66	72	71	70	75	67	66	68
1961	67	65	60	59	60	66	71	71	70	75	75	72	68
1962	71	66	64	59	62	69	70	70	73	71	69	69	68
1963	71	66	61	59	63	74	75	69	74	71	72	68	69
1964	67	66	66										
AVR.	69	66	62	61	62	69	72	70	72	73	71	69	68

TABLE 27 MONTHLY MEAN RELATIVE HUMIDITY 1600 HRS. (%) WATERFORD BARBADOS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959									67	71	73	69	
1960	64	59	62	64	61	67	70	71	70	75	68	64	66
1961	62	60	57	59	60	63	71	70	68	73	76	70	66
1962	67	66	64	58	62	67	70	66	69	70	69	70	66
1963	67	60	60	58	63	67	73	67	71	72	71	68	66
1964	63	61	62	65									
AVR.	65	61	61	60	62	66	71	68	70	72	71	68	66

FIG. 31 MONTHLY AVERAGES OF RELATIVE HUMIDITY (%) WATERFORD
BARBADOS
(January 1960 - December 1963)

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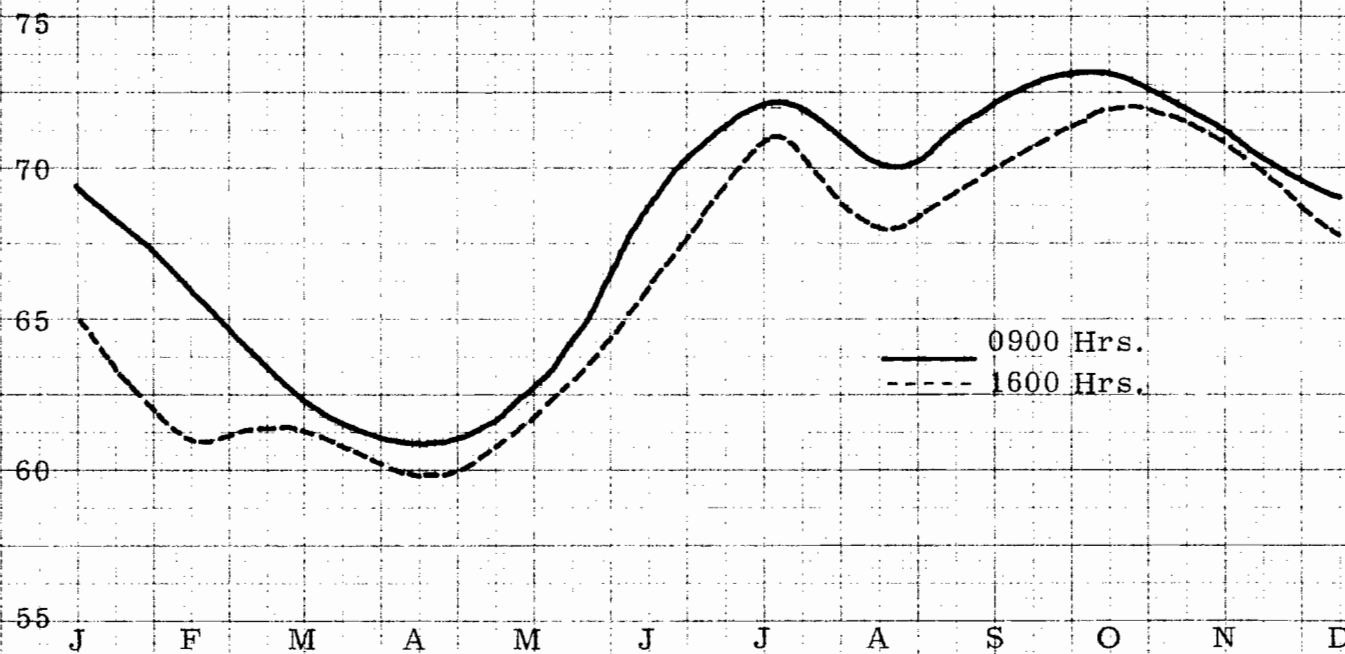
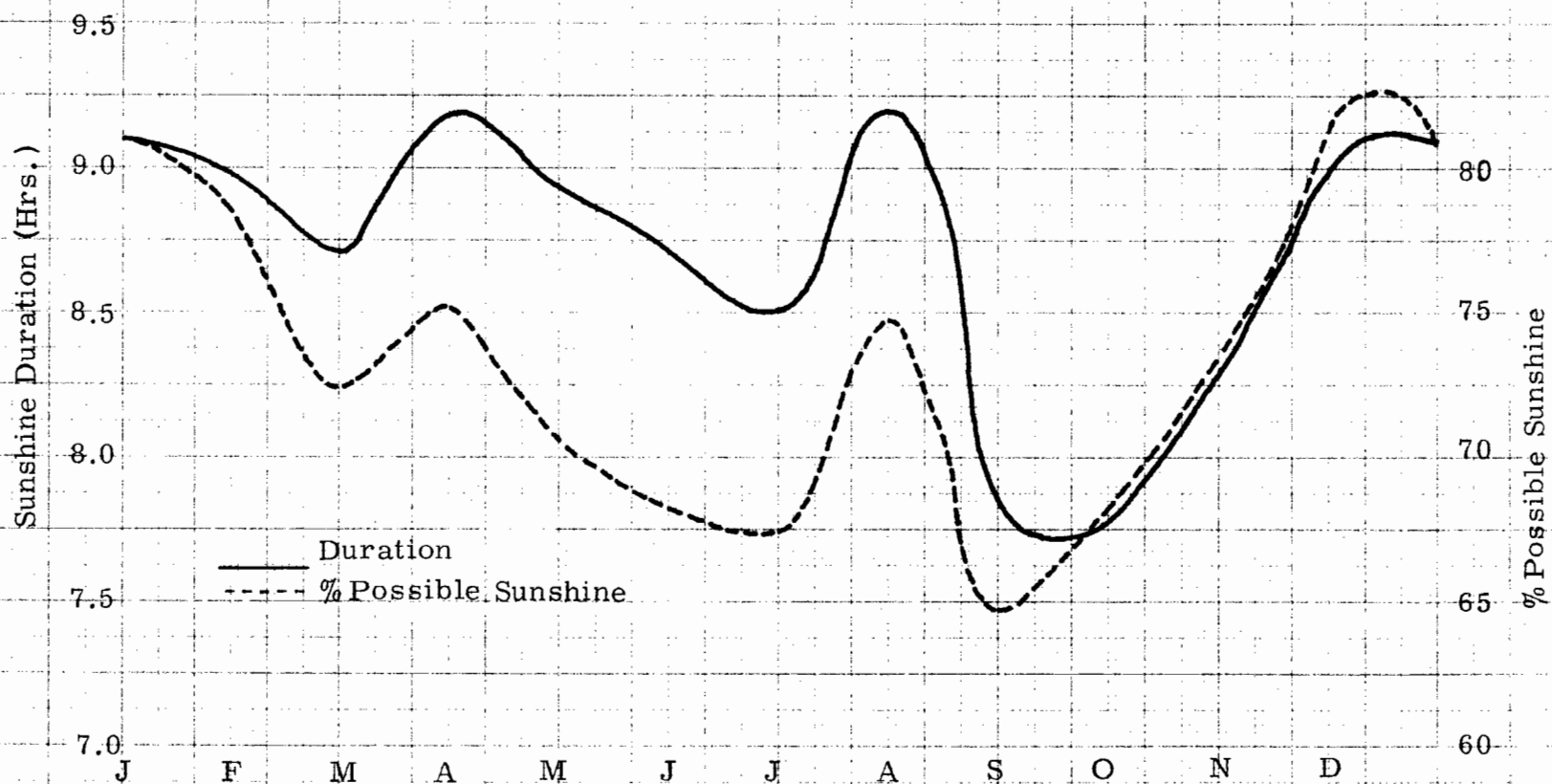


FIG. 32 MONTHLY AVERAGES OF HOURS OF BRIGHT SUNSHINE IN A DAY
CODRINGTON BARBADOS

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APRIL (9.2 hrs.) and AUGUST (9.2 hrs.) ; and the minima in MARCH (8.7 hrs.), JULY (8.5 hrs.) and SEPTEMBER/OCTOBER (7.8 hrs.).

The per cent of possible sunshine in a day follows more or less the same pattern. The only difference is that while the highest maximum occurs in APRIL in the case of actual sunshine duration, it occurs between DECEMBER and JANUARY in the case of per cent possible sunshine duration. Figures for sunshine duration can be found in Table 28.

VI SOIL TEMPERATURE (°F) WATERFORD BARBADOS

The annual average of soil temperature at 0900 hrs. is 80.2° F, 78.8° F and 79.6° F, at 2", 4" and 8" depth respectively. At 1600 hrs. they become 86.2° F, 85.1° F and 81.5° F. These are shown as temperature profiles in Fig. 33.

The seasonal march of soil temperatures is shown in Fig. 34, 35. The variation resembles that of seasonal march of surface temperatures (Fig. 4). There are two maxima and two minima. The maxima occur in MAY and AUGUST at all depths, both maxima being almost equal in magnitude except at 2" depth where they differ by about 1.5° F at 1600 hrs. The minima occur in JANUARY and JULY at all depths except at depths 2" and 4" at 1600 hrs. where the JANUARY minimum occurs in DECEMBER. The JULY soil temperatures are always the higher minima, exceeding the JANUARY minima by about 5.0° F. The 4" depth graph lies wholly below the 8" depth graph at 0900 hrs. At 1600 hrs. the reverse is the case.

TABLE 28 MONTHLY MEANS OF HOURS OF BRIGHT SUNSHINE WATERFORD BARBADOS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1959			8.7	8.7	8.1	8.8	9.1	9.5	8.7	7.0	8.3	9.3	8.7
1960	9.3	9.3	8.7	9.1	9.4	8.6	8.7	9.1	7.8	7.4	8.9	8.6	8.7
1961	9.6	8.2	8.9	9.8	9.8	8.8	7.8	8.8	8.3	7.1	7.5	8.9	8.6
1962	9.2	8.8	8.4	9.8	9.1	8.5	8.8	9.1	7.2	9.1	8.7	8.9	8.8
1963	8.4	9.6	8.8	8.8	8.1	8.9	8.0	9.6	7.1	8.3	8.0	9.1	8.6
1964	9.0	8.9	9.2										
AVR.	9.1	9.0	8.7	9.2	8.9	8.7	8.5	9.2	7.8	7.8	8.3	9.0	8.7

FIG. 33 ANNUAL AVERAGE SOIL TEMPERATURE PROFILE WATERFORD BARBADOS 109
(January 1960 - December 1963)

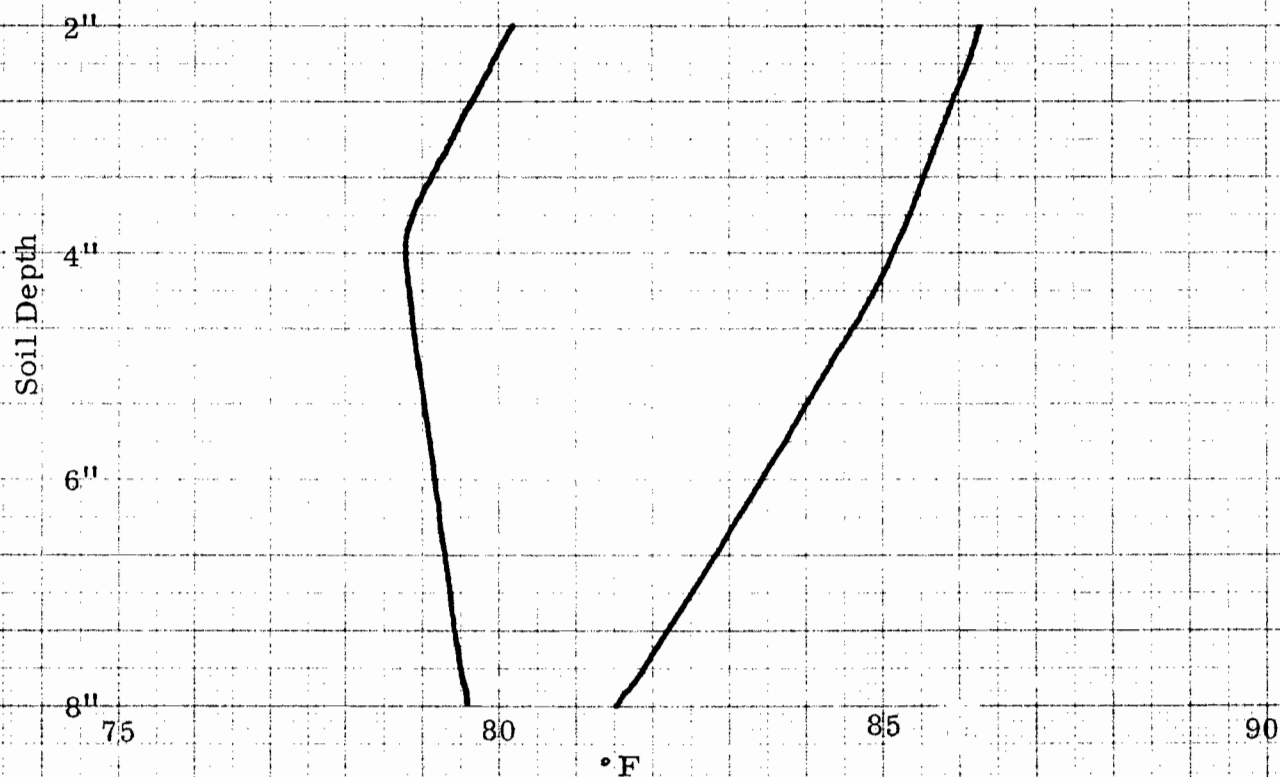


FIG. 34 MONTHLY AVERAGES OF SOIL TEMPERATURES (°F) 0900 HRS. WATERFORD
BARBADOS
(January 1960 - December 1963)

110

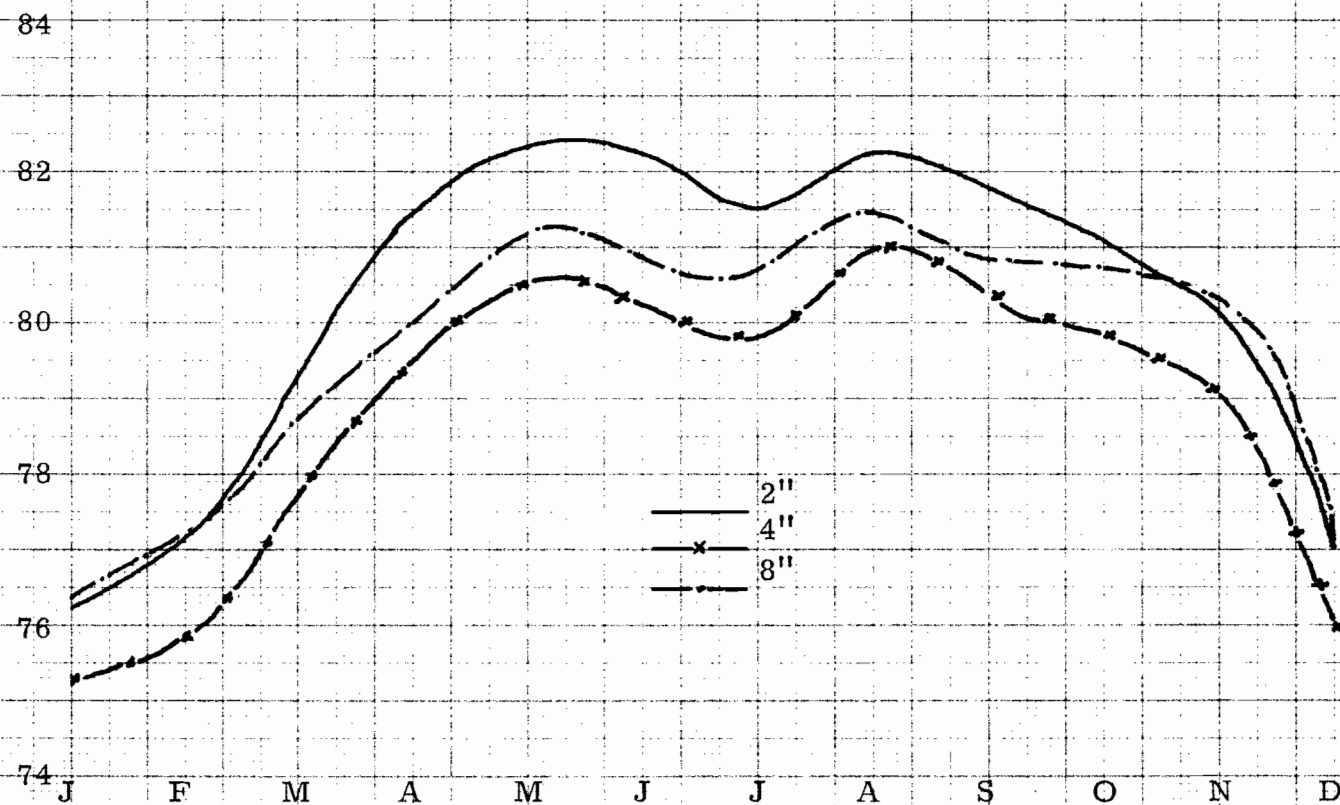


FIG. 35 MONTHLY AVERAGES OF SOIL TEMPERATURES (°F) 1600 HRS. WATERFORD
 BARBADOS
 (January 1960 - December 1963)

111

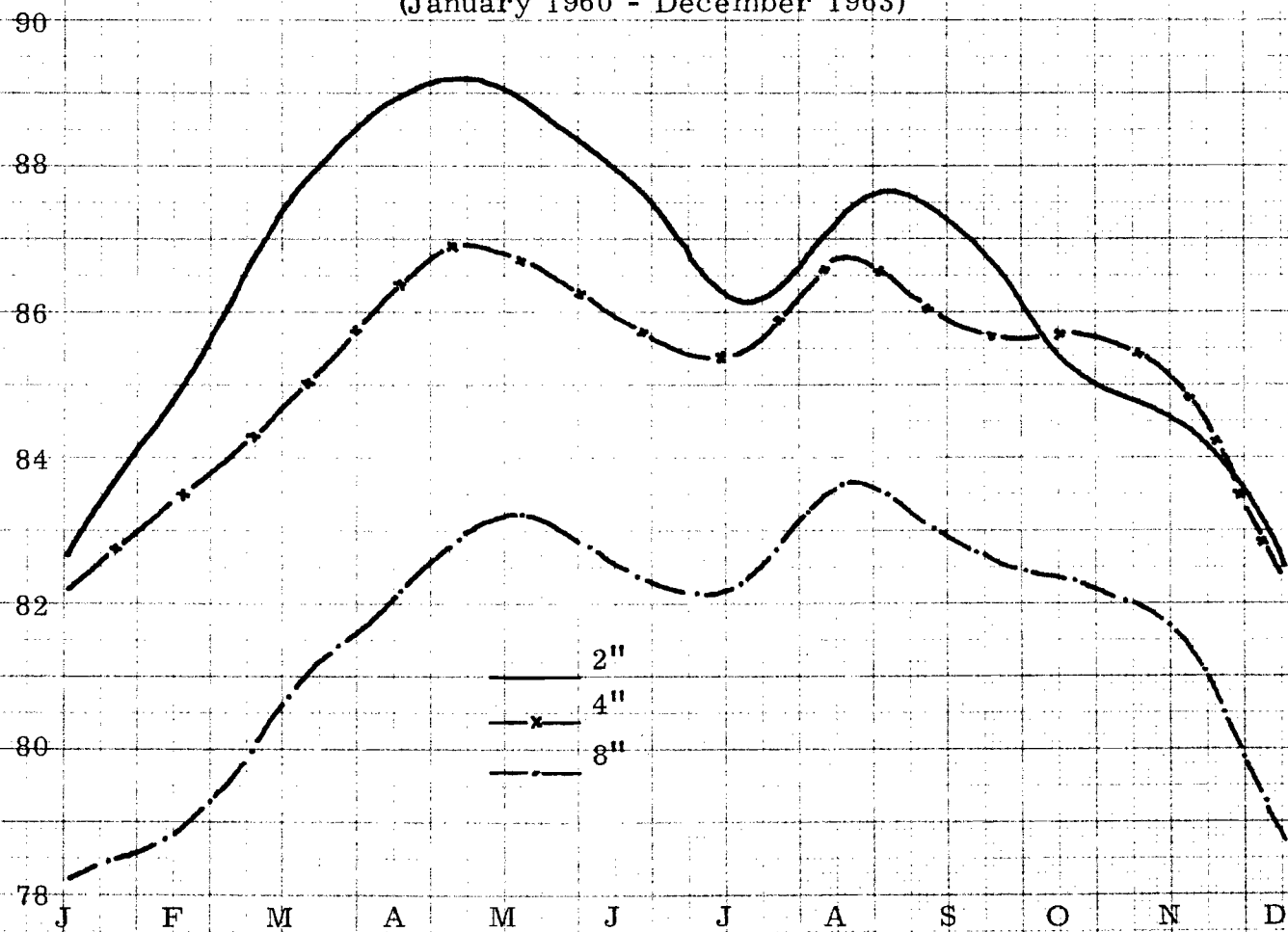


Fig. 36 shows profiles of soil temperatures for the month of JANUARY, APRIL, JULY and OCTOBER for 0900 hrs. and 1600 hrs. The 0900 hrs. profiles show a temperature minimum at 4" depth. It also shows a considerable warming from JANUARY to APRIL, and very little warming from APRIL to OCTOBER. The 1600 hrs. profiles show temperature minimum at 8" depth, but they show the same warming trend as at 0900 hrs.

Annual soil temperature range is larger than the annual air temperature range at all the three depths. At 0900 hrs. the annual temperature range is 6.0° F, 5.7° F and 4.6° F, at 2", 4" and 8" respectively. At 1600 hrs. the range is 6.5° F, 4.6° F and 5.4° F respectively. There is a marked decrease of annual range with depth at 0900 hrs. However, at 1600 hrs. there is a decrease down to 4" and then an increase down to 8", which is rather peculiar.

There is no time lag of the occurrence of either the maximum or the minimum with increasing depth as is normally observed (Landsberg, 1960).

Figures for soil temperatures are found in Tables 29, 30 and 31.

Figures 37 and 38 also show isopleths of monthly mean soil temperatures for Waterford for 0900 hrs. and 1600 hrs. respectively.

FIG. 36 PROFILES OF SOIL TEMPERATURES FOR SELECTED MONTHS WATERFORD
BARBADOS
(January 1960 - December 1963)

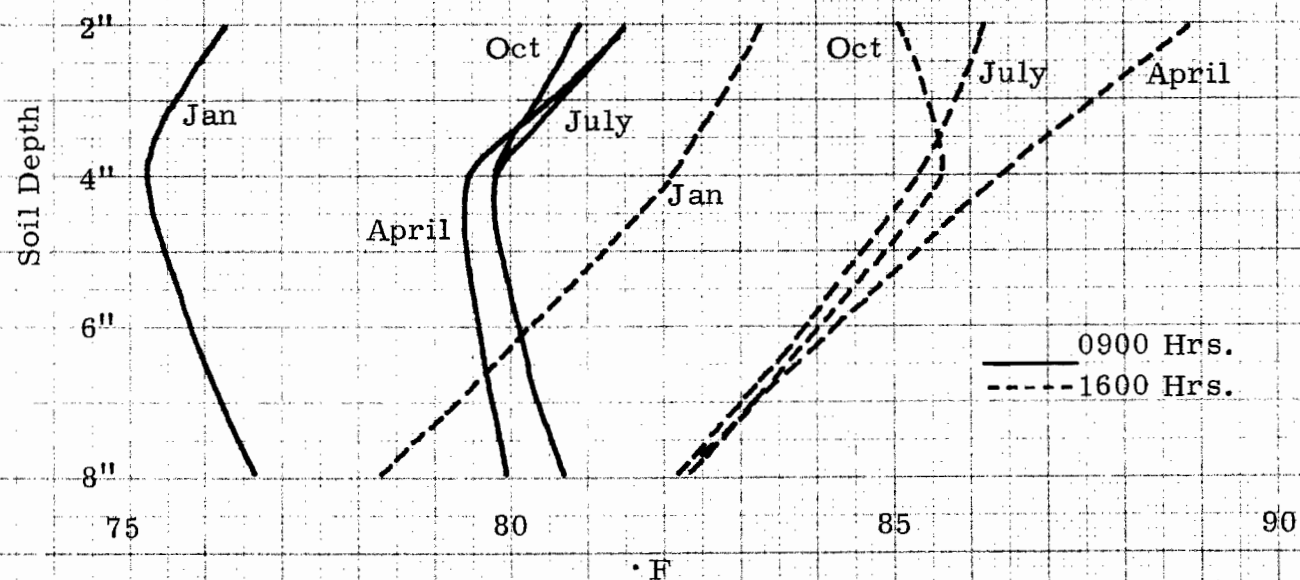


TABLE 29 MONTHLY MEANS OF SOIL TEMPERATURES 2" DEPTH WATERFORD BARBADOS
0900 HRS.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960	76.0	77.0	77.0	79.0	82.0	82.0	82.0	82.0	83.0	81.0	81.0	77.0	79.9
1961	76.0	76.0	79.0	82.0	82.0	83.0	80.0	82.0	82.0	79.0	81.0	77.0	79.9
1962	77.0	78.0	82.0	81.0	83.0	82.0	83.0	82.0	81.0	82.0	79.0	77.0	80.6
1963	76.0	77.0	79.0	84.0	82.0	82.0	81.0	83.0	81.4	81.8	79.8	76.9	80.3
1964	74.1	76.1	78.9	78.9									
AVR. 4 YR.	76.2	77.0	79.2	81.5	82.2	82.2	81.5	82.2	81.8	81.0	80.2	77.0	80.2

TABLE 29 (Continued)

1600 HRS.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960		87.0	86.0	88.0	90.0	88.0	88.0	87.0	89.0	85.0	88.0	85.0	87.0
1961	85.0	85.0	88.0	89.0	90.0	89.0	84.0	88.0	89.0	82.0	83.0	82.0	86.2
1962	83.0	87.0	91.0	89.0	90.0	87.0	88.0	87.0	85.0	86.0	83.0	80.0	86.3
1963	82.0	84.0	85.0	90.0	86.0	86.0	85.0	88.0	87.0	88.0	84.8	83.0	85.7
1964	81.2												
AVR.	82.8	85.1	87.5	89.0	89.0	87.5	86.2	87.5	87.5	85.2	84.7	82.5	86.2

TABLE 30 MONTHLY MEANS OF SOIL TEMPERATURES (°F) 4" DEPTH WATERFORD BARBADOS

0900 HRS.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960	75.3	76.0	77.0	78.0	81.0	80.0	80.0	80.0	80.0	80.0	79.0	76.0	78.5
1961	75.0	75.0	77.0	79.0	81.0	81.0	79.0	81.0	80.0	78.0	79.0	76.0	78.4
1962	75.0	76.0	79.0	79.0	80.0	80.0	80.0	81.0	80.0	80.0	79.0	76.0	78.8
1963	76.0	76.0	78.0	82.0	80.0	80.0	80.0	82.0	81.3	81.3	79.3	76.6	79.4
1964	74.3	76.3	78.4	79.0									
AVR.	75.3	75.8	77.8	79.5	80.5	80.2	79.8	81.0	80.3	79.8	79.1	76.0	78.8

TABLE 30 (Continued)

YEAR	<u>1600 HRS.</u>												ANNUAL
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
1960	82.3	83.0	83.0	85.0	87.0	87.0	87.0	87.0	87.0	88.0	87.0	83.0	85.5
1961	83.0	83.0	85.0	86.0	87.0	87.0	85.0	87.0	86.0	84.0	85.0	83.0	85.1
1962	82.0	84.0	86.0	87.0	87.0	85.0	85.0	84.0	84.0	84.0	84.0	80.0	84.3
1963	82.0	84.0	85.0	89.0	86.0	85.0	85.0	89.0	86.7	87.4	84.4	82.6	85.5
1964	80.6	82.9	84.5	84.0									
AVR.	82.3	83.5	84.8	86.5	86.8	86.0	85.5	86.8	85.9	85.8	85.1	82.2	85.1

TABLE 31 MONTHLY MEANS OF SOIL TEMPERATURES (°F) 8" DEPTH WATERFORD BARBADOS

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960		78.0	78.0	79.0	82.0	81.0	81.0	81.0	81.0	81.0	81.0	78.0	79.8
1961	77.0	77.0	79.0	80.0	81.0	81.0	80.0	82.0	81.0	79.0	80.0	77.0	79.5
1962	76.0	77.0	79.0	80.0	81.0	80.0	81.0	81.0	80.0	80.7	79.0	77.0	79.3
1963	77.0	77.0	79.0	81.0	81.0	81.0	80.7	81.3	81.0	82.0	80.1	77.6	79.1
1964	75.4	77.1	79.1	79.4									
AVR.	76.4	77.2	78.8	80.0	81.2	80.8	80.7	81.3	80.8	80.7	80.2	77.4	79.6

TABLE 31 (Continued)

1600 HRS.

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960		79.0	80.0	82.0	84.0	83.0	83.0	83.0	84.0	83.0	83.0	80.0	81.9
1961	79.0	79.0	81.0	83.0	84.0	83.0	82.0	84.0	83.0	80.0	82.0	78.0	81.5
1962	78.0	79.0	82.0	82.0	83.0	82.0	82.0	84.0	82.0	82.4	80.0	78.0	81.2
1963	78.0	78.0	80.0	82.0	82.0	82.0	82.3	83.7	82.7	84.3	82.1	79.4	80.6
1964	77.3												
AVR.	78.3	78.8	80.8	82.2	83.2	82.5	82.3	83.7	82.9	82.4	81.8	78.8	81.5

FIG. 37 ISOPLETHS OF SOIL TEMPERATURES (°F) WATERFORD, BARBADOS
(January 1960 - December 1963)
0900 Hrs.

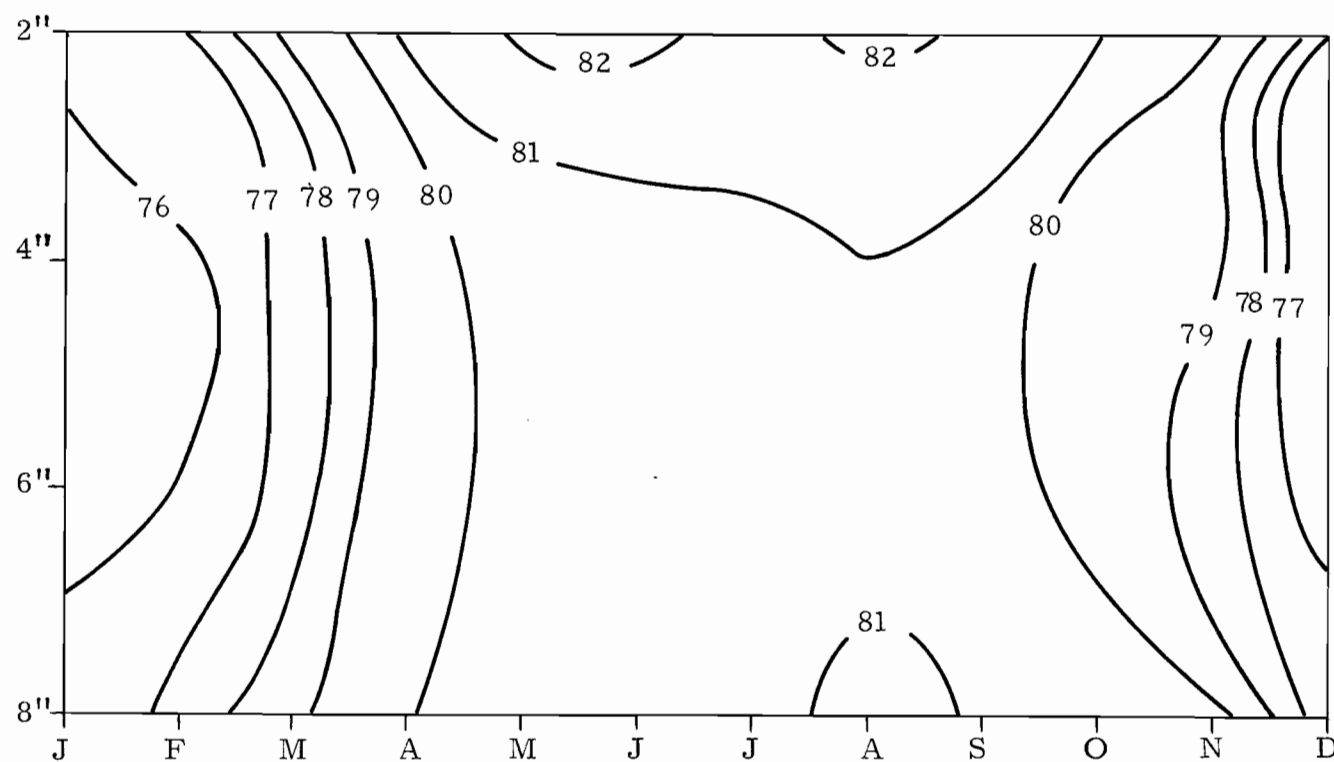
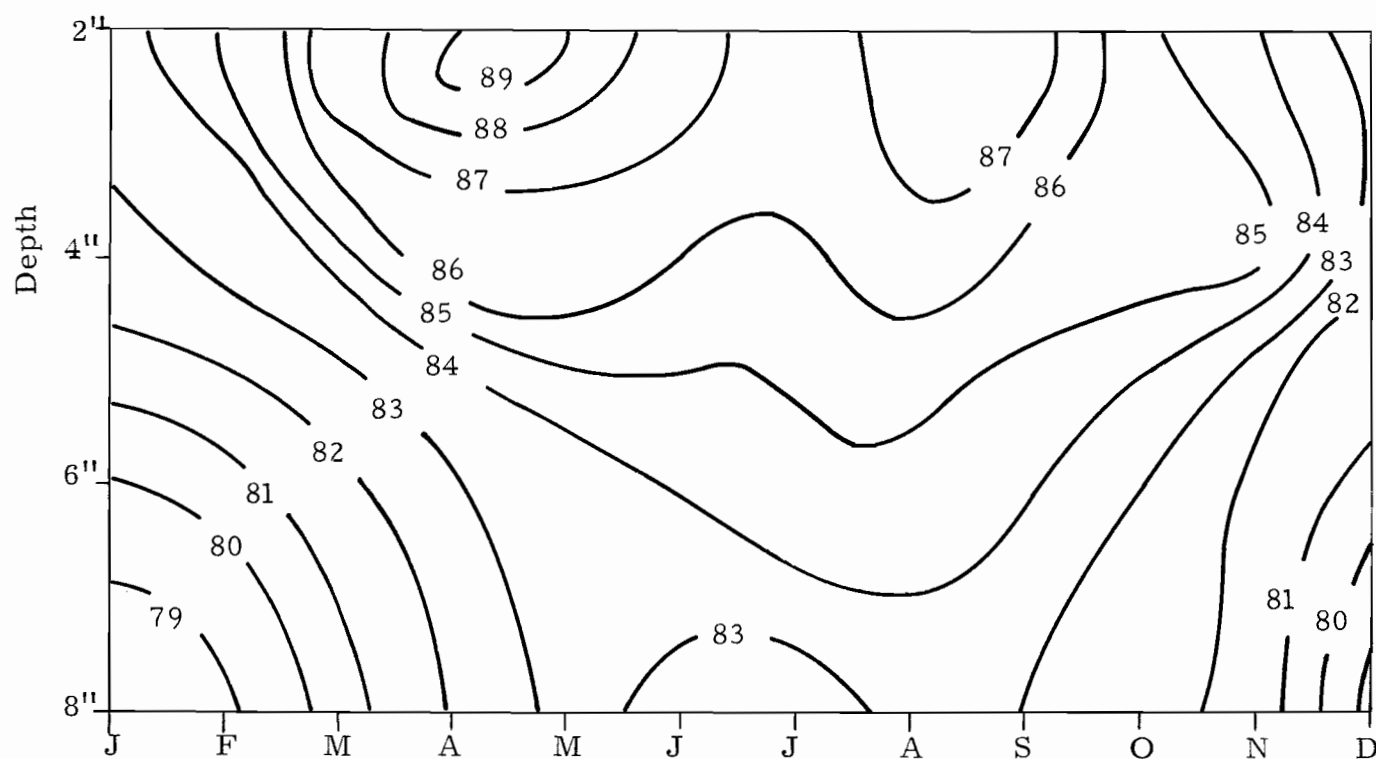


FIG. 38 ISOPLETHS OF SOIL TEMPERATURES ($^{\circ}$ F) WATERFORD, BARBADOS
(January 1960 - December 1963)
1600 Hrs.



VII GRASS MINIMUM TEMPERATURE (°F)

WATERFORD BARBADOS

The annual average grass minimum temperature is 66.6°F. The lowest minimum occurs in FEBRUARY (62.0°F). The seasonal variation is of the same pattern as minimum air temperature (Fig. 6), except that there are two distinct maxima in JUNE and OCTOBER . The annual range of grass minimum temperature is 8.6°F, indicating the greatest seasonal variation of the elements considered so far. Figures for grass minimum are found in Table 32 and their seasonal variation is shown in graph in Fig. 39.

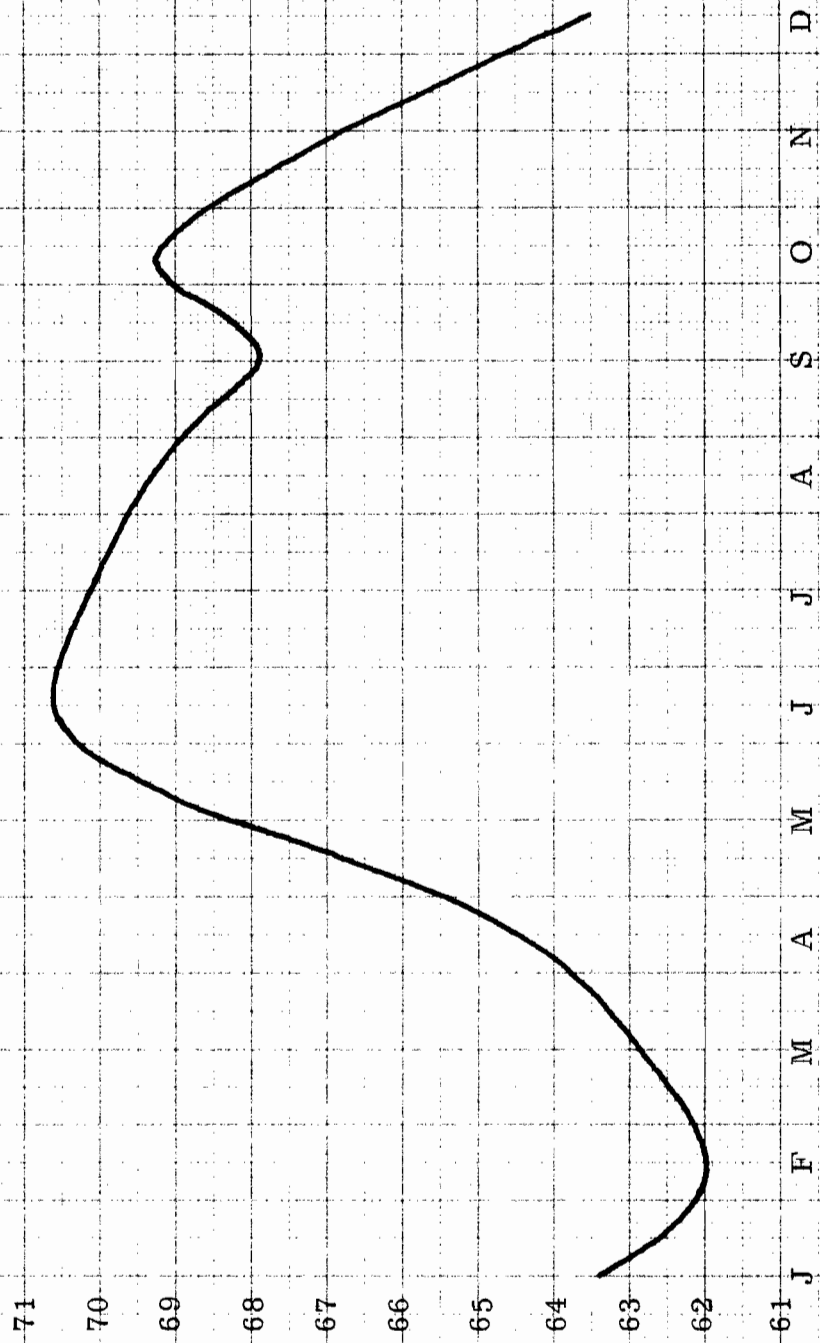
TABLE 32 MONTHLY MEANS (°F) GRASS MINIMUM TEMPERATURE WATERFORD

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
1960	62.1	60.3	61.5	64.3	68.3	70.5	70.3	70.1	67.7	69.9	65.9	63.8	66.4
1961	63.6	62.5	62.5	63.7	68.1	70.1	70.1	70.6	67.7	72.6	67.5	61.2	66.6
1962	65.4	64.2	62.4	65.4	67.9	70.8	69.9	68.3	68.4	67.1	65.7	64.5	66.6
1963	62.7	61.2	66.0	63.9	68.3	70.8	70.0	68.4	68.2	67.6	67.4	64.6	66.6
1964													
AVR.	63.4	62.0	63.1	64.4	68.2	70.6	70.1	69.4	68.0	69.3	66.6	63.5	66.6

FIG. 39

WATERFORD

FIG. 39 GRASS MINIMUM TEMPERATURE (°F) WATERFORD BARBADOS
(1960 - 1963)



J F M A M J J A S O N D

CHAPTER III

SYNOPTIC CLIMATOLOGY

I DEFINITION

Synoptic Climatology may be defined as "an attempt to describe the totality of weather over a region as a function of the atmospheric circulation." (Walker, 1961) The method consists of breaking down the fictitious mean climatic picture into the actually occurring weather patterns of which climate is composed, and relating such patterns to some specification of the atmospheric circulation. It is because the specifications of the atmospheric circulation (e.g. pressure patterns) are derived from weather maps rather than from spot measurements like the ordinary weather elements that the approach is called Synoptic Climatology. (Jacobs, 1947 ; Landsberg, 1960)

II VARIOUS APPROACHES

Centres of Action Approach

Koppen (1874) attempted to relate climate to the positions of high and low pressure systems, their intensities and movements. He had very little success.

Airmass Approach

This approach is an attempt to relate the local weather to the airmass. The approach is somewhat out of date ; nevertheless, it is

climatologically useful and revealing, at least, in giving some understanding of the large-scale climatic features caused by the general circulation and its variations. (Landsberg, 1960) The first attempt of this approach was by Bergeron (1930), who described the climate in terms of air masses. The result was a presentation of climate which was less static than the classical presentation.

Dinies in 1932 made a serious attempt of this approach by presenting the climate of Germany as a buildup of the characteristics of the various air masses. He presented frequencies of the different air masses and then obtained average values of temperature, humidity and cloudiness in each type of air mass. His treatment did present the month or season "as one of change and conflict" (Durst, 1951). In the next ten years Dinies's example was followed by others including Landsberg (1937) who examined air masses of central Pennsylvania. The air mass approach was developed with little success owing to difficulties inherent in air mass analysis (Durst, 1951).

Pressure Pattern Approach

This approach relates the local weather to circulation pattern by the use of synoptic pressure patterns as a basis for climatic classification. This line of approach involves classifying every weather map situation for a given area according to types and then summarizing the climatic elements according to these types. Quite apart from the

labour that is involved there is much subjectivity involved in typing the pressure patterns, and also a large number of types is necessary to describe the local weather or climate. It is this subjectivity in typing the pressure patterns that forced Jacobs to abandon this method (Jacobs, 1946). This is not surprising because the task of relating pressure pattern to day-to-day weather is not always a straightforward one. This is a problem not only in Synoptic Climatology but also in both short and long range forecasting. Though a prognosis may be perfect, two experienced forecasters will interpret the pressure patterns differently in terms of concurrent weather. The question that always faces the forecaster and the climatologist is this: "What specific weather does a pressure chart indicate?" (Martin, 1950).

Little work has been done in this direction in relating weather to the large-scale features of the pressure pattern on a day-to-day basis. The Extended Forecast Section of the U.S. Weather Bureau has done some investigation relating 5-day average weather in terms of quantitative values of temperature and precipitation to the large-scale pressure pattern of the same period. (Martin, 1950; Hawkins, 1950)

However, this subjective approach has been used by Hare in describing the climate of Southeast Asia. Hess and Brezowsky have also adopted this method for describing the climate of Central Europe for a period of 67 years. (Landsberg, 1960)

The large-scale pressure patterns can, however, be classified objectively. This is achieved by representing the pressure field mathematically "by fitting an ensemble of Tchebysheff orthogonal polynomials to the marginal sums of pressure over a region which is subdivided into a gridwork of equally spaced sampling points. The coefficients of these functions characterize the particular pressure pattern over a given major section of the globe." (Friedman, 1955)

"The coefficients of these functions characterize, for example, the pressure patterns over a given major sector of the globe. It is quite conceivable that frequencies of combinations of these coefficients will be the replacement for the subjective map typing now needed in this approach to a dynamic climatology." (Landsberg, 1960)

Airflow Approach

This approach relates the observed weather to the direction of air flow over the region in question. The regions are divided into relatively small areas (100,000 - 200,000 square miles) such that the air flow can be represented by a single wind vector at the free atmosphere. Climatic data are then classified according to the different flow patterns. Though the approach is objective to some extent, the results of the studies by the Extended Forecast Section of the U.S. Weather Bureau suggest that features of the circulation pattern many thousands of miles away may contain information relevant to the

specification of the local weather, even on a day-to-day basis. Herein lies the weakness of this approach of considering small areas; however, some amount of success was achieved by Jacobs (1946,1947) in using this method. Walker (1961) also used this method in studying the Synoptic Climatology of British Columbia.

III APPROACH ADOPTED

The approach adopted in this thesis is not, strictly speaking, Synoptic Climatology. It only seeks to give explanatory notes on the causes of the seasonal variation of climate by means of mean maps rather than Synoptic maps. This may give the impression that the climate in Barbados is static and that the synoptic map can be explained in terms of the mean maps, a notion commonly held by those living outside the Tropics. Any familiarity with Tropical climate or synoptic maps will show that the climate or weather in a month or in a season is not one of long monotony, but of "change and conflict," though the degree of change may not be the same as in Temperate Climate.

In order not to give this impression an attempt will also be made to demonstrate the fact of aperiodic changes of climatic elements from day-to-day, with particular reference to temperature and rainfall, and suggest causes where possible, of such changes.

In the following is given the description of the major controls of the seasonal variations of climate in Barbados.

IV CONTROLS OF CLIMATE

(i) Apparent Movement of the Sun

The apparent movement of the sun is the ultimate control and explanation of seasonal variation of climate. Overhead, the sun reaches its zenith over Barbados twice a year, at the end of April and at the end of July.

(ii) Sea-level Pressure

The main features of importance are the ridge of high pressure around 30° N, commonly known as the "Sub-tropical High," and the zone of low pressure around the equator called the "doldrums" or the "equatorial trough." Figs. 40 and 41.

During the N. H. Summer (July) the N. Atlantic and N. Pacific subtropical highs appear as two distinct cells, whereas the S. Atlantic and S. Pacific highs form an almost uninterrupted belt. During the N. H. Winter (January) the reverse is the case.

The centres of the Sub-tropical highs move very little with the seasons. The movement is about 5° Lat. Table 31 (after Hauwitz and Austin, 1944) shows the mean positions of their centres and also the mean values of their central pressures in January and July.

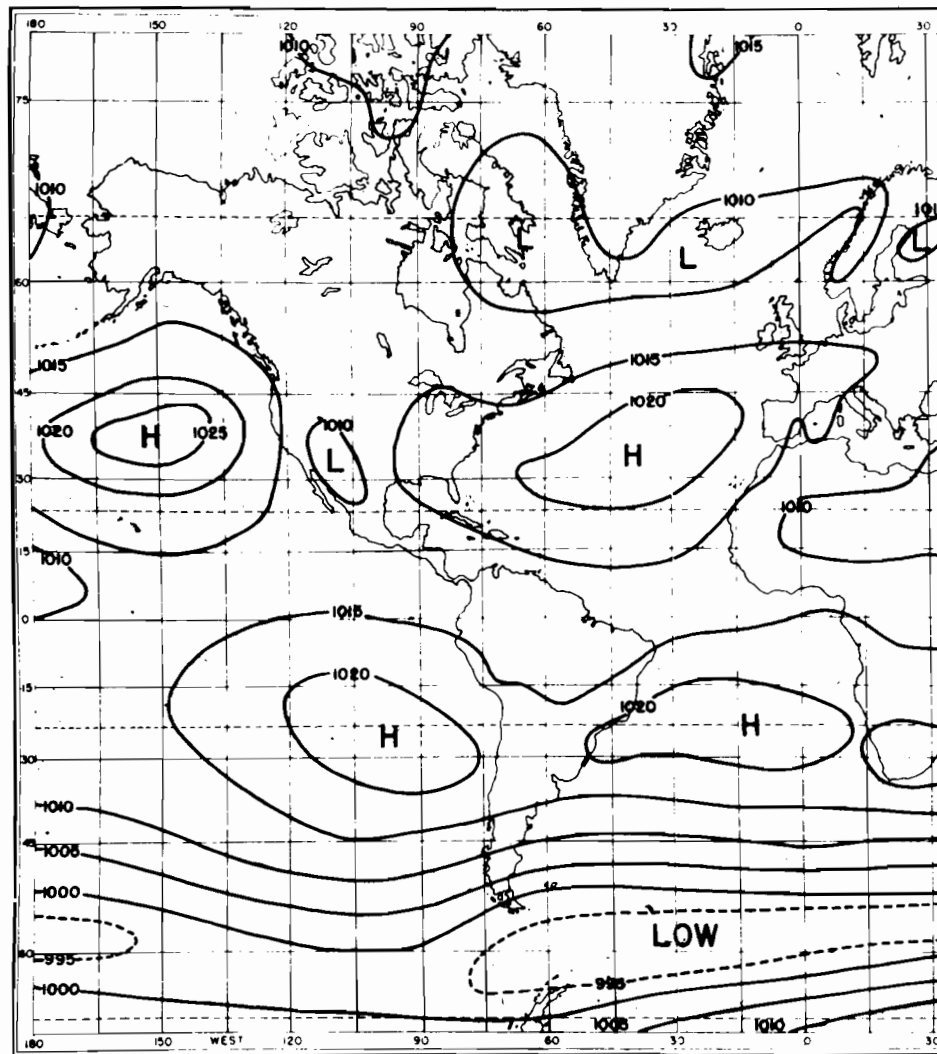


FIG. 40 MEAN SEA LEVEL PRESSURE (mb.) IN JULY
(After Haurwitz and Austin, 1944)

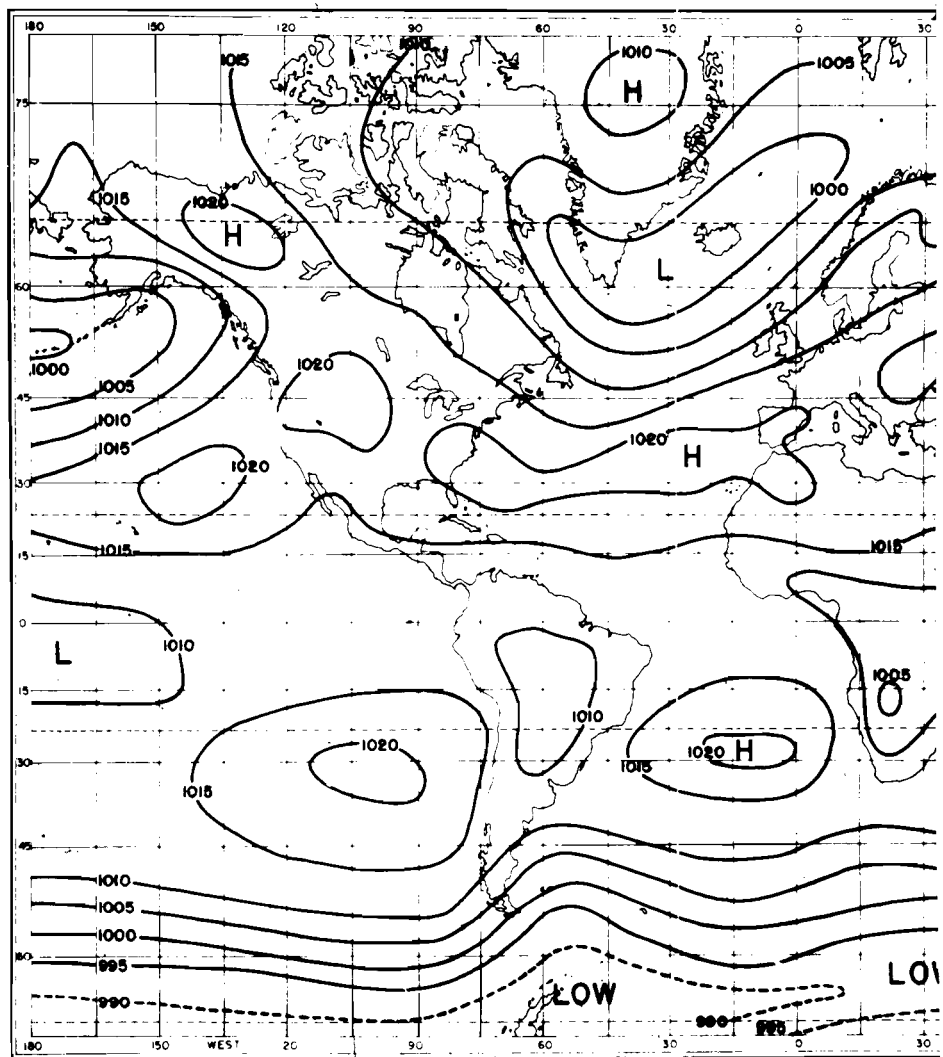


FIG. 41 MEAN SEA LEVEL PRESSURE (mb.) IN JANUARY
(After Haurwitz and Austin, 1944)

TABLE 31

	JANUARY		JULY	
	Position	Pressure (mb)	Position	Pressure (mb)
<u>N. H.</u>				
N. Atl. H.	34° N	1022	36° N	1025
N. Pac. H.	28° N	1022	39° N	1027
<u>S. H.</u>				
S. Atl. H.	28° S	1021	23° S	1024
S. Pac. H.	32° S	1021	26° S	1024

Notice a distinct difference between the two hemispheres.

In the N. H. the central pressures are higher in summer than in winter while in the S. H. the opposite is the case. However, in both hemispheres the Sub-tropical highs are nearer the equator in winter than in summer, a very significant factor in the explanation of the seasonal variations of the meteorological elements, especially the wind regime and the large-scale inter actions of disturbances in the mid-latitudes and in the trades. (Malkus, 1962)

The Equatorial Trough is a zone or region of low pressure in between the Sub-tropical highs in the Northern Hemisphere and Southern Hemisphere. The central pressure is more or less uniform and hovers around 1010 mb. Notice (Figs. 40 and 41) that the equatorial trough is joined to the thermal lows over the continents during summer. The

position of the Trough is not confined to the Equator all the year round. Unlike the Sub-tropical highs, the Equatorial Trough varies widely north and south seasonally. Moreover, the amount of seasonal variation of its position varies sharply around the globe. Over the region of Barbados the variation, seasonally, amounts to only 5° Lat. This is typical of western hemisphere Equatorial Trough. In contrast, the Trough oscillates more than 30° L in the eastern hemisphere. Fig. 42 (after Rhiel) shows the mean position of the equatorial trough for January and July. The longitude in which Barbados is situated is marked with an arrow. Fig. 42 is, however, an underestimate of the oscillations of the Equatorial Trough since in most places, including Barbados, its extreme position occurs in August/September and February. The migration of the Trough in relation to Barbados is an important factor in understanding the seasonal variation of its climate because, generally speaking, the equatorial trough is a zone of cloudiness, rainfall and tropical storms.

(iii) Upper Level Pressure

No mean pressure maps for upper levels were available to the writer; however, owing to latitudinal temperature differences we expect the centre of the Sub-tropical highs to slope equatorward with height, the slope being strongest in winter.

FIG. 42 MEAN POSITIONS OF THE EQUATORIAL TROUGH

(After Riehl, 1954)

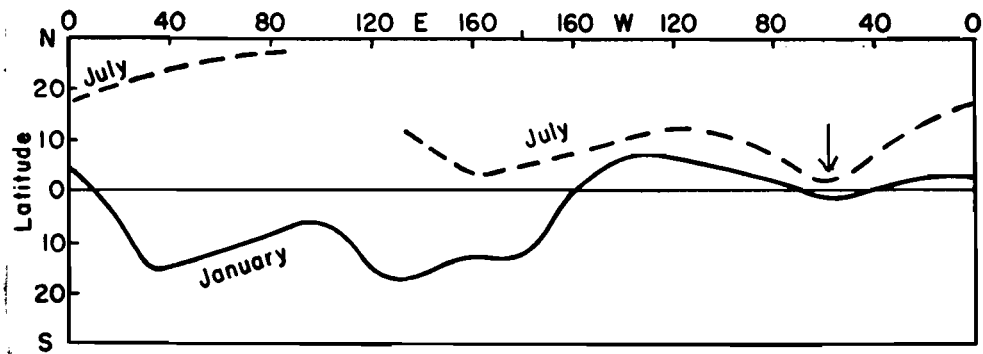
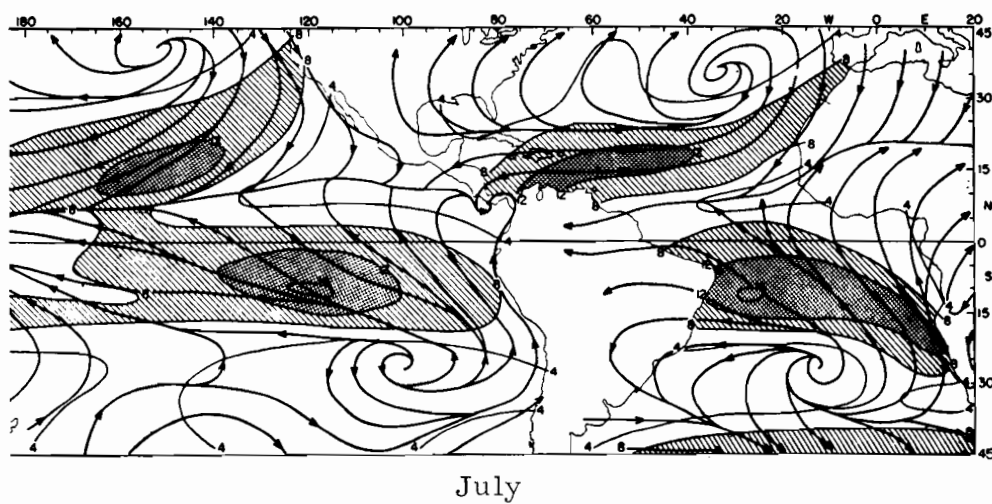
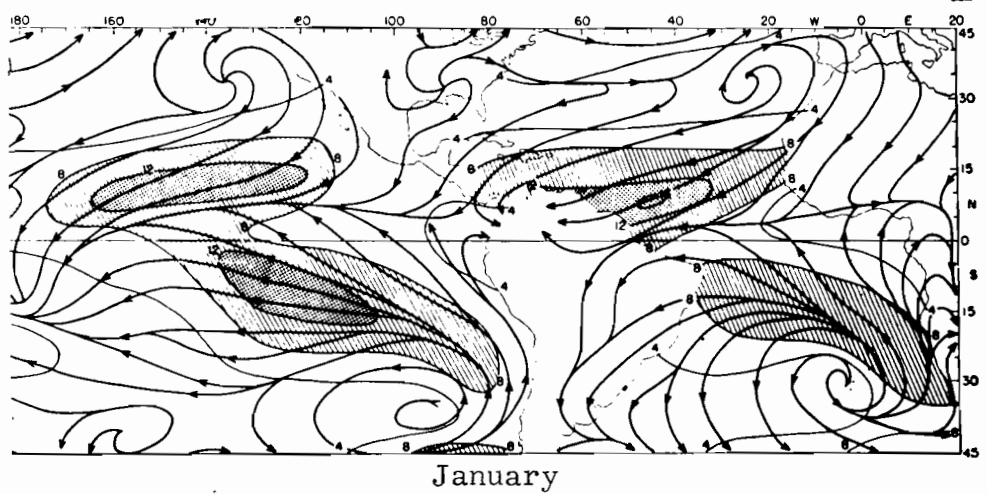


FIG. 43 RESULTANT STREAMLINES AND ISOTACHS

(After Riehl, 1954)



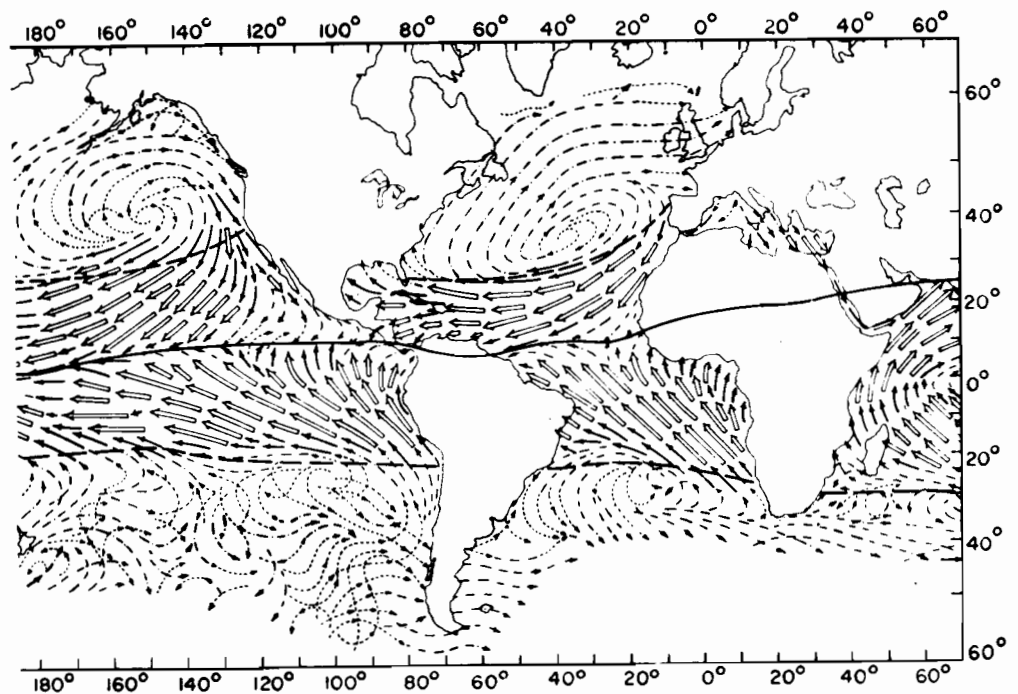
Light shading denotes areas with wind speed greater than 8 kts;

Heavy shading, greater than 12 kts.

FIG. 44 PREVAILING SURFACE WINDS OVER THE OCEANS

IN SUMMER JULY

(After U.S. Weather Bureau)



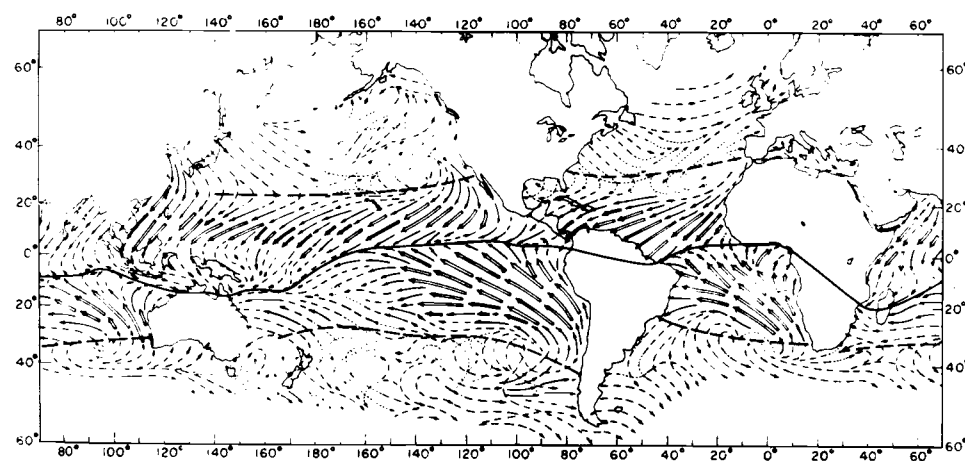
Steadiness: $\Rightarrow$ 81% and over ; $\longrightarrow$ 61-80% ;
 $\dashrightarrow$ 41-60% ; $\cdots\rightarrow$ 25-40%

Solid line is the mean position of the equatorial trough.

Dashed lines are mean positions of Sub-tropical ridge.

FIG. 45 PREVAILING SURFACE WINDS OVER THE OCEAN IN WINTER
JANUARY

(After U.S. Weather Bureau)



Steadiness: The same symbols as in Fig. 44.

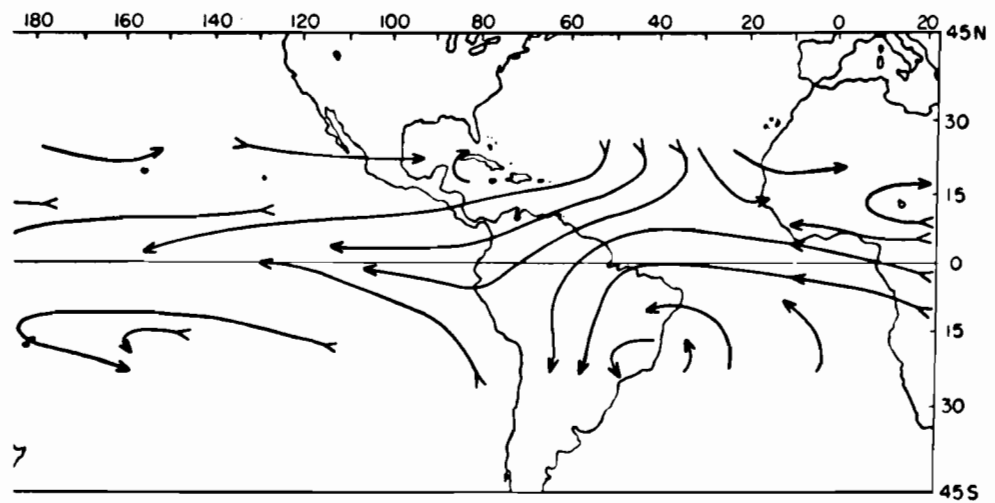
The persistency of wind is therefore seen to be quite high in Barbados. This places Barbados in the Trade Wind region. However, the Trade Wind region is not characterized by only high persistency of wind, but also by a large meridional wind component, a comparatively strong meridional temperature gradient, typical antitrades aloft, marked subsidence aloft, and a low and strong Trade Wind inversion. (Palmer, 1951) The frequency of occurrence of such characteristics over Barbados will determine, to a large extent, the prevailing weather, and hence determine the broad features of the seasonal variation of its climatic elements.

(v) Upper Winds

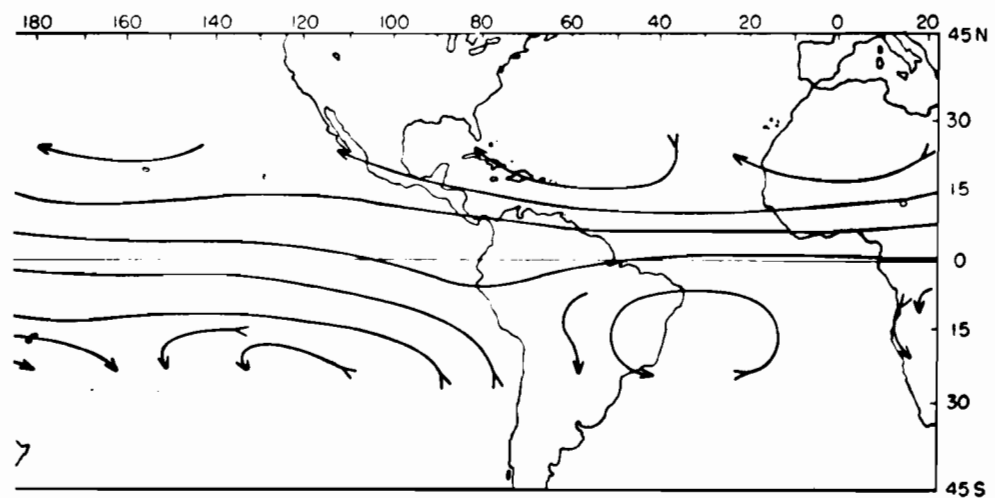
The Sub-tropical ridge slopes towards the equator with height leading to a corresponding tilt in the boundary between the polar westerlies and the equatorial easterlies, so that the westerlies overlie the easterlies in some parts of the Tropics. The seasonal shift of the entire system towards the equator in winter results in wide variations in depth of the easterlies, at least at stations 10° or more from the equator.

Figs. 46 and 47 show upper level maps after British Met. Office. The mean circulation at 700 mb resembles that at the surface in both winter and summer, except that the strong equatorial component of the surface flow, though present in winter, is absent in summer.

FIG. 46 MEAN CIRCULATION AT 700 mb. (After British Met. Office)

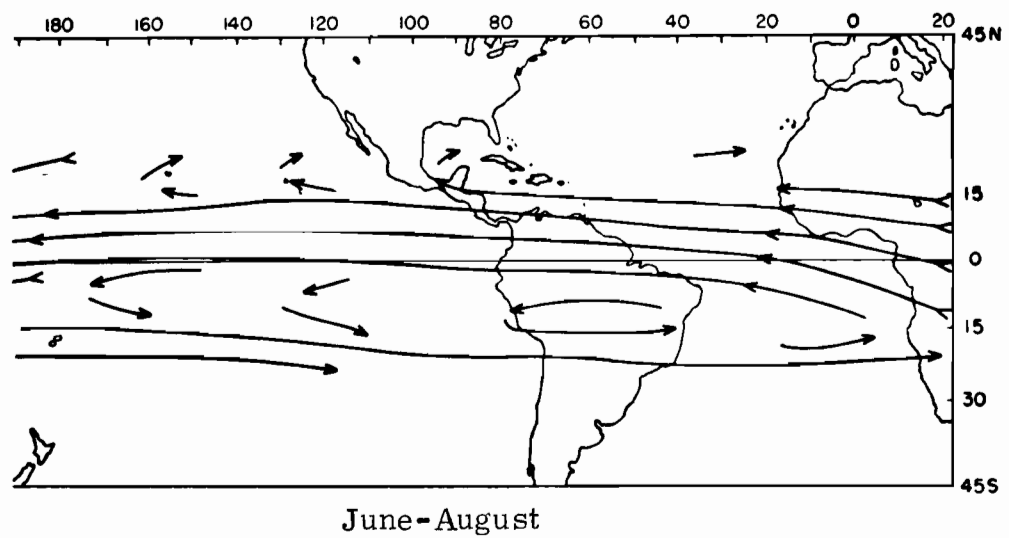
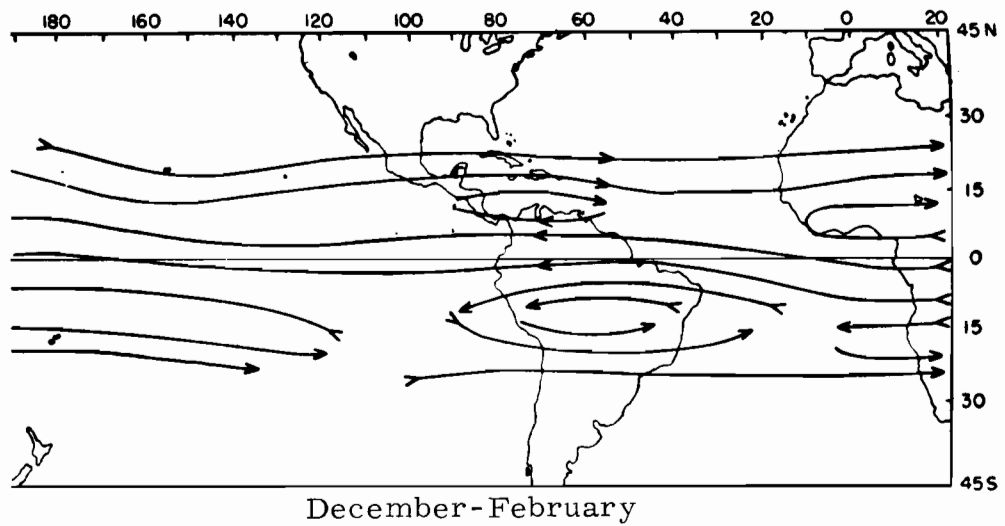


December-February



June-August

FIG. 47 MEAN CIRCULATION AT 300 mb. (After British Met. Office)



In summer the flow has a slight poleward component. Also there is no streamline convergence anywhere as is the case on the surface. At 300 mb. the flow departs more radically from the surface flow. There is neither an equatorial flow nor streamline convergence in the equatorial trough. In the Northern Hemisphere the Sub-tropical high appears as an east-west elongated circulation at about 13° L in winter. It is missing in summer due to lack of observations. In the Southern Hemisphere it is located at 15° L throughout the year. The polar westerlies can be seen to be present as far equatorward as 15° S.

The mean upper level circulation over Barbados can be summarized as follows:

	700 mb.	300 mb.
Winter	ENE	W
Summer	E	E

A more detailed wind analysis in the Caribbean is presented by Colon (1962). Though the data analysis is based on only one month of observations (December, 1956), it is typical of the mean conditions in winter over the Caribbean (Fig. 48). It gives a more detailed insight not only on streamline flow but also on the strength and persistency of the wind and their variation with height. The wind speed and direction over Barbados at 850 mb. and 200 mb. are given as follows:

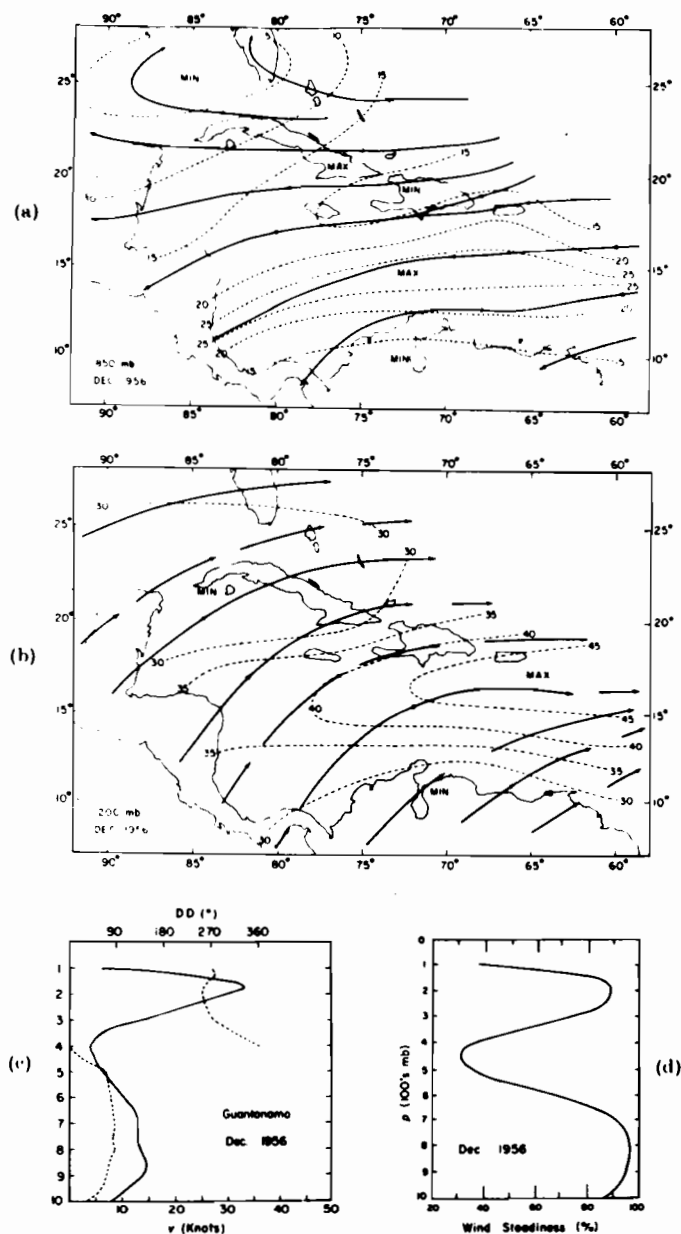


FIG. 48 CIRCULATION OF WIND OVER BARBADOS IN WINTER
 (After Colon, 1960. Figs. 3, 4 and 7)

- (a) The low level flow patterns at 850 mb. (5000 ft.)
 ———> streamlines; ...>... isotachs.
- (b) The high level flow patterns at 200 mb. (40,000 ft.)
- (c) Typical vertical wind profile with height. (The sounding is for Guantanamo in Cuba)
- (d) Vertical profile of directional wind steadiness in percentage. Ordinate is pressure in 100's of mb. (Guantanamo).

850 mb. (5000 ft.)		200 mb. (40,000 ft.)	
Direction	Speed	Direction	Speed
ENE	20 kts.	SW	40 kts.

The vertical profile of wind speed, direction and persistency presented in Fig. 48 is for Guantanamo in Cuba. They are presented by Colon as typical of the Caribbean area. The easterlies are seen to be fairly strong and steady; they vary little in both speed and direction up to 400 mb. The layer 400 mb. - 300 mb. is a transitional layer where the easterlies change rapidly into the polar westerlies, and the winds become very unsteady. The polar westerlies are strongest and steadiest at 200 mb. It is highly probable that the above profiles may represent conditions over Barbados except that the easterlies will be stronger, the westerlies weaker, and the transitional zone slightly higher, because Barbados is nearer the equator than Guantanamo.

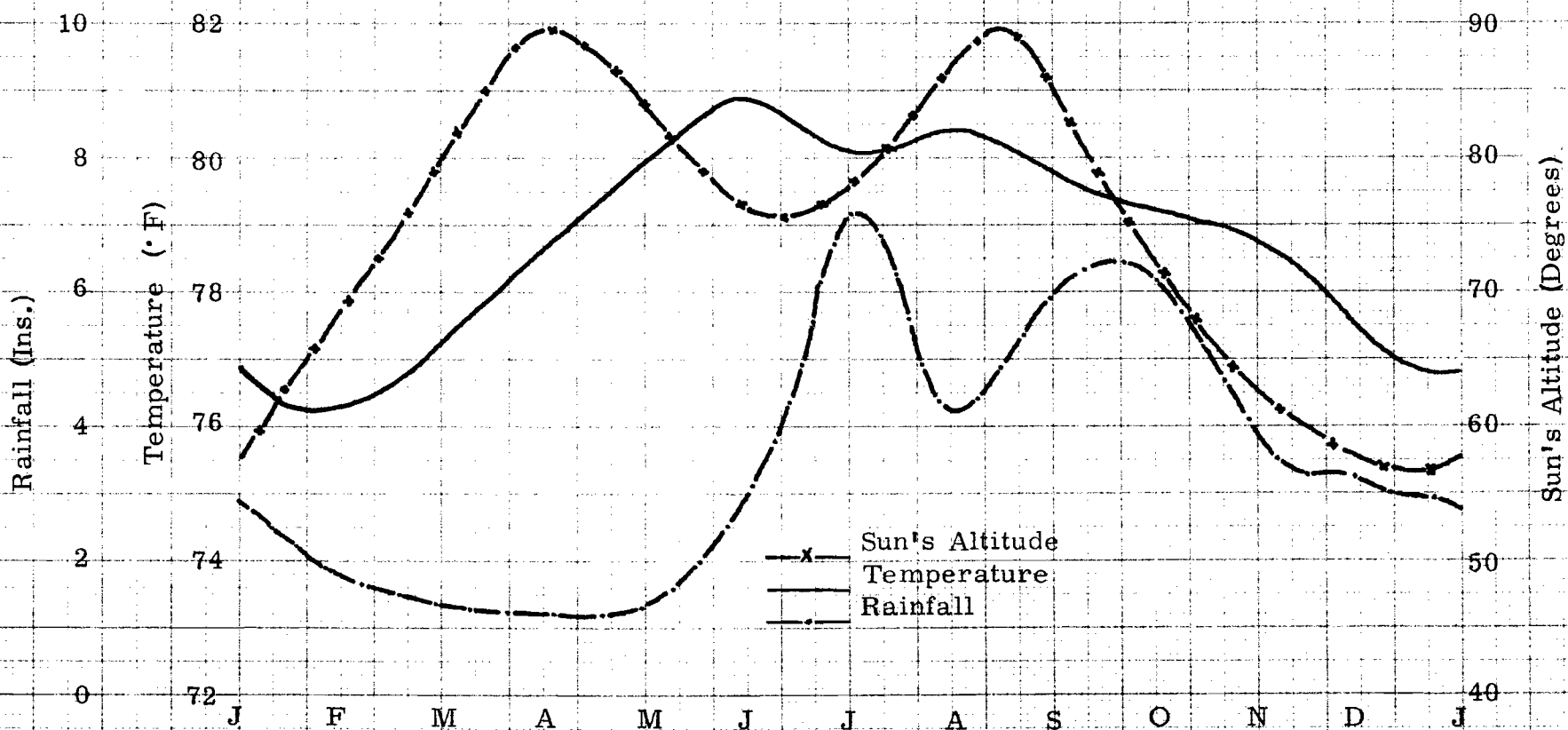
V CAUSES OF TEMPERATURE VARIATION

(i) Seasonal Variation

Atmospheric temperature is controlled mainly by the surface temperature and hence by the incoming solar radiation. The seasonal variation of temperature at a place will therefore be controlled, in general, by the annual variation of incoming solar radiation and therefore by the variation of the altitude of the sun at noon. Fig. 49 shows

FIG. 49 THE SUN'S ALTITUDE AT NOON, DAILY MEAN TEMPERATURE AND MONTHLY TOTALS OF RAINFALL WATERFORD, BARBADOS

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the seasonal variation of the daily mean temperature and that of the sun's altitude at noon for Waterford. The pattern of the two curves look fairly alike except that there is a lag in time of occurrence of extremes. The temperature maximum is reached two months after the sun has reached its first maximum altitude in April. Similarly the temperature reaches its minimum value one month after the sun has reached its lowest height in June, and also in January. The difference in time of occurrence of their extremes is simply due to the time it takes the earth's surface to warm up or cool down. The lag will therefore be less in continental areas than in oceanic areas. According to Landsberg this lag is about three weeks in continental areas and may reach six weeks in oceanic stations (Landsberg, 1960). This is in agreement with the above lag for Waterford which is an oceanic station.

It will be noticed that the second temperature maximum occurs about one month before rather than after the occurrence of the second highest point of the sun at the beginning of September. This is so because a simple rise and fall of temperature as the sun advances and recedes in the sky is not always enough to explain the temperature climate of a location. A combination of other factors like cloudiness and rainfall lead to conditioning the temperature climate. Cloudiness and rainfall tend to lower temperature by cutting off insolation, by the evaporation of raindrops, by downdraft if rainfall is convective, and by the wetting of the ground.

In Fig. 49 it is seen that the monthly mean rainfall begins to rise sharply from May, reaching a maximum in July. During that period the temperature reaches its maximum in June and begins to decrease. The cause of this downward trend of temperature is due, not only to the sun's altitude that is decreasing, but also to the increasing amount of rainfall. It may be that rainfall and cloudiness are the major contributing factors during this period because the temperature continues the downward trend so long as the rainfall continues in the upward trend until it reaches its minimum at the same time as the rainfall reaches its maximum in July. After July the sun is on its way to a second maximum altitude while the rainfall begins to decrease, both trends being in favour of temperature rise. Hence the temperature begins to rise, but it will be noticed that there appears to be a premature end in the rise in August though the sun's altitude continues to increase. This is so because the downward rainfall trend changes to an upward trend and thereby suppresses the temperature rise. In the meantime the sun reaches its highest point and begins to fall at the end of August, so that with the increase in rainfall and decrease in the sun's altitude the temperature continues to fall until the rainfall reaches its maximum in the middle of September. As the rainfall begins to decrease and the sun's altitude continues to decrease, the downward trend of the temperature is

halted or rather slowed down until about the middle of October or the end of November when it begins to fall again. This is so because the effect of decreasing rainfall and therefore of cloudiness in allowing the temperature to rise is about the same as the effect of the decreasing sun's altitude in causing the temperature to fall, until the end of November when the sun's altitude becomes the sole controlling factor.

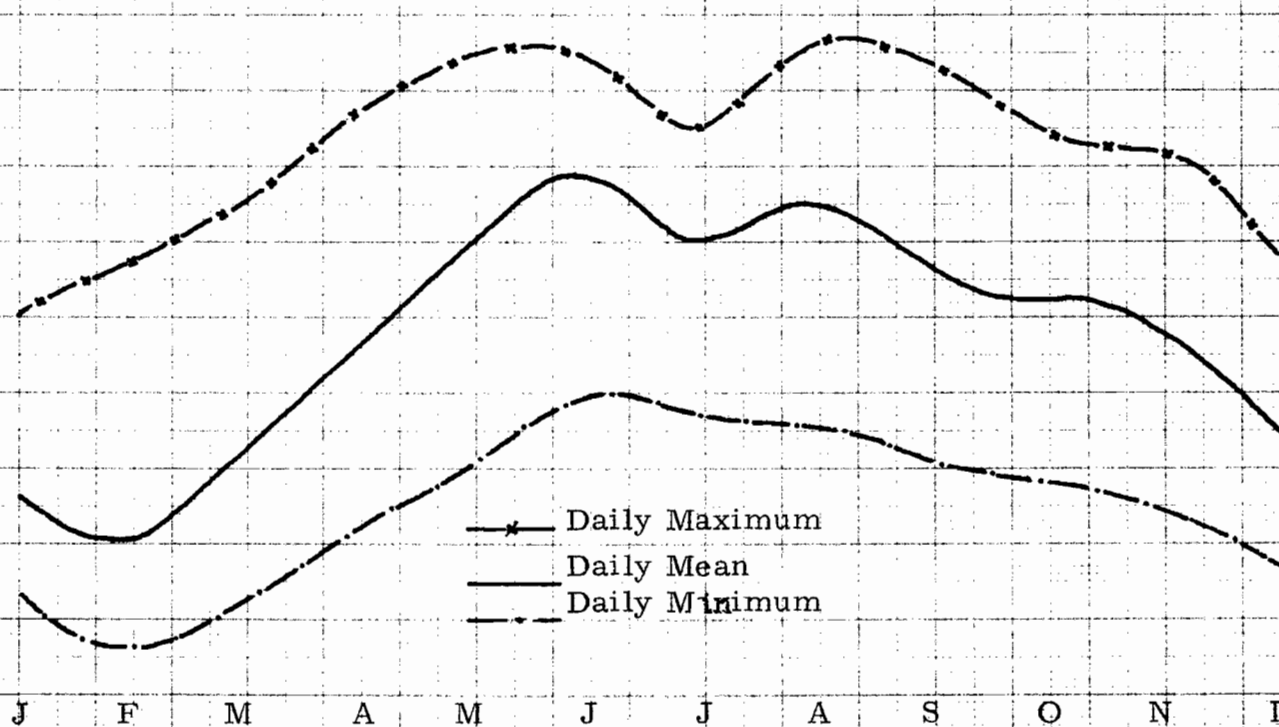
Solar radiation may therefore be said to be the controlling factor in the dry season and rainfall in the wet season. The rainfall curve during the rainy season runs inversely to the temperature curve. This is common to some of the stations in the equatorial regions. (Riehl, 1954) It may be added that it is the maximum temperature that is largely affected by rainfall and cloudiness and that largely determines the annual course of the daily mean temperature. Though minimum temperatures are also affected by reduced nocturnal radiation, a rise in minimum temperature comparable to a drop in maximum temperature is not known (Riehl). Compare curves for maximum, minimum, and daily mean temperatures in Fig. 50. It will be seen that it is the maximum temperature that resembles daily mean temperature curve more closely during the rainy season.

(ii) Day-to-day Variations

Though the seasonal course of temperature shows a smooth

FIG. 50 COMPARISON OF SEASONAL VARIATION OF MAXIMUM, MINIMUM AND DAILY
MEAN TEMPERATURES WATERFORD, BARBADOS
(March 1959 - February 1964)

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variation from month to month there are day-to-day irregular variations within a month or a season. The process of averaging over a month has smoothed out such aperiodic day-to-day variations. Taking the month of January 1962 at Waterford as an example, the average interdiurnal temperature changes for this month turns out to be 1.2°F . Though this factor is small compared with middle latitude values (e.g., England, also having an oceanic climate, has an average interdiurnal temperature change of 3.8°F in winter), yet within this month there were six occasions when the interdiurnal temperature change exceeded 2°F and three occasions when it exceeded 3°F . When such changes occur in combination with other factors they are sufficient to make an impression on the man in the street. Detailed analysis of such aperiodic temperature changes are given on pages 34 - 46.

The causes of such changes in temperature are due not only to general synoptic conditions but also to local factors. Any attempt to assess the causes of such changes will involve not only the study of day-to-day synoptic changes but also micrometeorological changes. However, an attempt is made in this thesis only to indicate some of the possible causes of such aperiodic changes. Below are outlined some of the possible causes.

a) Large scale changes in the circulation strength

Changes in the strength of the Trade Wind are associated

with the changes in position and strength of the Sub-tropical high pressure cells. Periods of one week to several weeks occur when the Sub-tropical high becomes elongated and intensified, resulting in a large pressure gradient equatorward. A period of "high index" is said to exist when the easterlies are strong with speeds greater than 12 - 14 kts., zonally uniform, and without any invasion of weather disturbances. At the start of the "high index" accelerations of the trades occur equatorward resulting in "surges of the trades" with speeds of about 30 - 50 mph. over wide areas of the oceans and lasting perhaps for 2 - 4 days. This results in rapid advection of cool air and subsequent fall of temperature and sometimes squalls. These "high index" periods alternate with periods of "low index" when the Sub-tropical high is weak and elongated meridionally, thus resulting in weaker trades, with speeds less than 12 - 14 kts., and disrupted by frequent disturbances. (Malkus, 1962, Riehl, 1954)

The two years wind data available for Waterford do not show such "surges."

b) Sea breeze

Another cause of fluctuations in the day-to-day temperatures is the sea breeze. Waterford is about two miles from the sea and comes under the moderating influence of the sea with reduction in noon temperatures. Though sea breeze can be very regular at Water-

ford, its intensity and therefore the amount by which the noon temperature is reduced is likely to vary from day-to-day. This is quite conceivable because the formation of the sea breeze depends not only on the differential heating of land and water but also on the strength of the prevailing wind, which is subject to variations. The temperature changes will be relatively pronounced on days when a cold-front-like sea breeze breaks through and invades the land. (Defant, 1951) Fig.51 (after Defant) is a schematic diagram of a cold-front-like sea breeze.

When the interaction of the sea breeze and trades takes place on land, convection, cloudiness, and rain may result, thereby reducing further the temperature.

c) Weather disturbances

Weather disturbances almost invariably produce cloud and rain, especially when the disturbance contains a squall line. Quite apart from the reduction in temperature that results from cloudiness and evaporation of raindrops, strong downdrafts or squalls can reduce temperatures considerably.

d) Lapse rate of temperature

The daily temperature maximum is affected by the stability of the air. With a strong inversion, which is usually low, there is limited mixing and so a small mass of air is heated during the day, resulting in higher maximum temperature. This will be more pro-

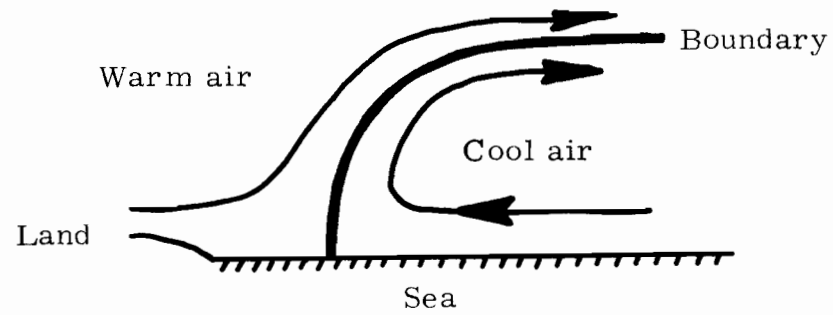


FIG. 51 COLD-FRONT-LIKE SEA-BREEZE (After Defant)

nounced if the wind is not too strong. The trade wind inversion is not present from day-to-day, neither does its intensity and height remain the same. There are variations in its frequency and characteristics. (Gutnick, 1958) This is likely to contribute to the aperiodic variations of the daily mean temperature.

VI CAUSES OF SEASONAL VARIATION OF RAINFALL

Rainfall is the most variable of all meteorological elements, whether during the rainy season or the dry season even in the tropics, and Barbados is no exception. An attempt is made to examine some of the various factors that are commonly held to control the seasonal variation of rainfall in the tropics and to determine which ones are likely to control the rainfall regime of Waterford in particular, and Barbados in general.

(i) Sun's altitude or Solar Radiation

Fig. 49 shows that the seasonal variation of the sun's altitude has no obvious relation with the seasonal variation of rainfall. It is not sufficient to say that there is an obvious relation but that they differ only in time of occurrence of their extremes, for two reasons. 1. Why should the sun reach its first maximum altitude and then its first minimum altitude before the first rainfall maximum occurs, and why does

the same amount of lag not occur at the subsequent extremes? 2. Not all stations in Barbados have double maximum rainfall regime. Stations quite close to Waterford like Codrington Agricultural Station and Belle Factory (Fig. 52) have only one maximum rainfall regime. The annual course of rainfall as a simple function of latitude cannot therefore explain the seasonal variation of rainfall at Waterford.

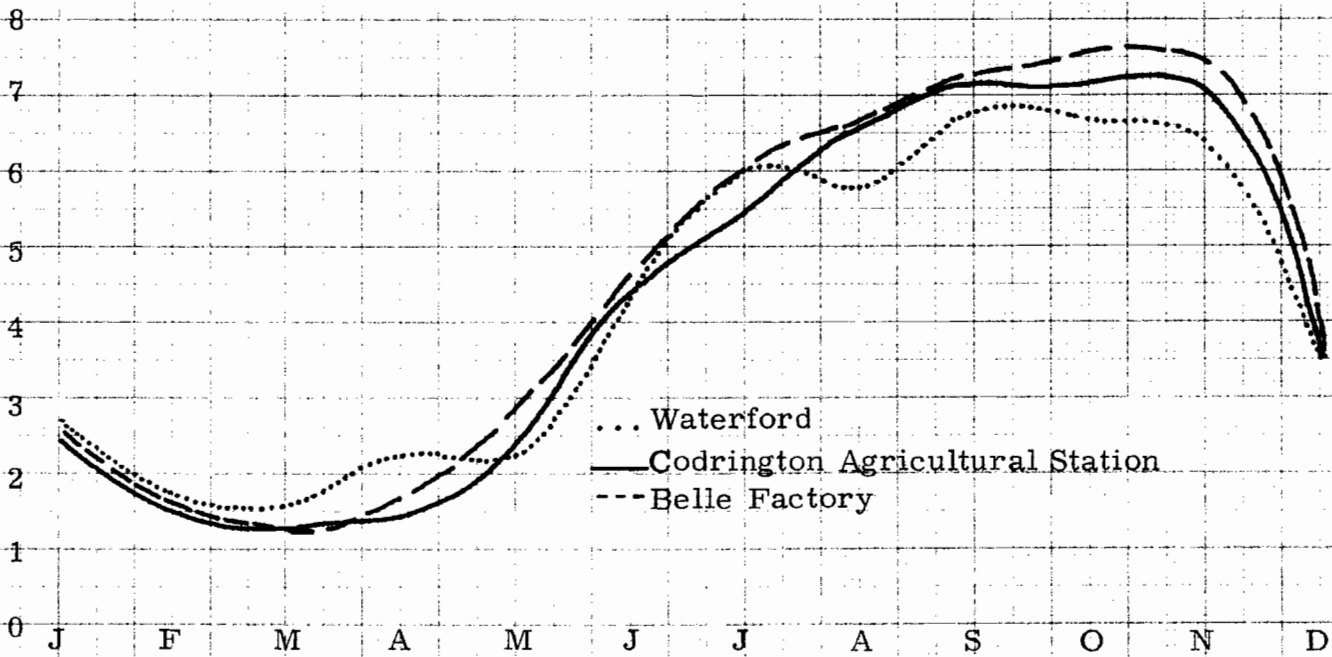
(ii) Equatorial Trough

It is commonly held that the rainfall regime at a location in the tropics is controlled by the seasonal variation of the equatorial trough with respect to the location. It is also held that because the equatorial trough is regarded as a region of convergence, heating, cloudiness and rain, there ought to be a two maximum rainfall regime, when it crosses the particular location twice in the year.

There are some difficulties in accepting the above simple explanation of rainfall regime at Waterford.

a) Double maximum rainfall regime occurs in Barbados at locations which are interspersed with those having single maximum. If the migration of the equatorial trough is the controlling factor, then the Island, being small, should be under its control simultaneously and therefore the same seasonal pattern of rainfall should prevail in the whole Island.

FIG. 52 RAINFALL (INS.)



b) The equatorial trough over the Caribbean area (Fig. 42) oscillates very little throughout the year. A regular double passage of the trough with the seasons is not observed. Rather an equatorial trough type of circulation frequently overlies Barbados and Trinidad in the Lesser Antilles in September, and sometimes in the North East Caribbean as late as early October. (Riehl, 1954) Therefore the equatorial trough as a control of rainfall regime of Waterford is contradicted by observations. It is this remarkably small annual march of the equatorial trough in some parts of the Tropics, among other factors, which forced Rossby to reject his direct cell model of the tropical circulation. (Palmer, 1951)

c) Even if the equatorial trough was observed to cross Barbados twice, synoptic experience and climatic data show that rainfall does not occur continuously because of the presence of an equatorial trough. There are periods of cloudiness and rain and periods of their cessation within the equatorial trough. The same is true of the Indian monsoon (Rahmattullah, 1952). The presence of the equatorial trough does not guarantee convergence. It is rather the statistical average that gives a net convergence. In some areas in the Pacific Ocean there is actually a net divergence in the equatorial trough in both January and July. (Byers, 1959)

d) Out of twenty-one rainfall regimes examined in Barbados

nine had their maximum occurring in November. This does not coincide with the latest time the equatorial trough is observed in Barbados, which is early October. (Fig. 53)

In view of the above four reasons it appears that the equatorial trough is not the direct control of rainfall regime of Waterford, though it may be indirectly.

(iii) Trade Wind Inversion

The Trade Wind inversion acts as a strong lid in opposing vertical cloud development. Since Barbados is situated in the Trade Wind region, the inversion may have some control on its rainfall regime. Fig. 54 is a schematic diagram of vertical cross-section along the path of the Trade Wind. (after Malkus)

Gutnick (1958) has produced a paper on the climatology of the Trade Wind inversion in the Caribbean. His graphs of Trade Wind frequency for Trinidad are compared with the rainfall curve for Waterford. His graphs for Antigua have the same trend as those for Trinidad and therefore Barbados is likely to have the same trend.

Fig. 55 shows that during the dry season the frequency of inversions is high and during the rainy season it is low. Fig. 56 shows similar trend for the strength of the inversions, the strongest inversion occurring during the dry season and the weakest during the rainy season. Fig. 57 shows that the base of the inversion is highest during



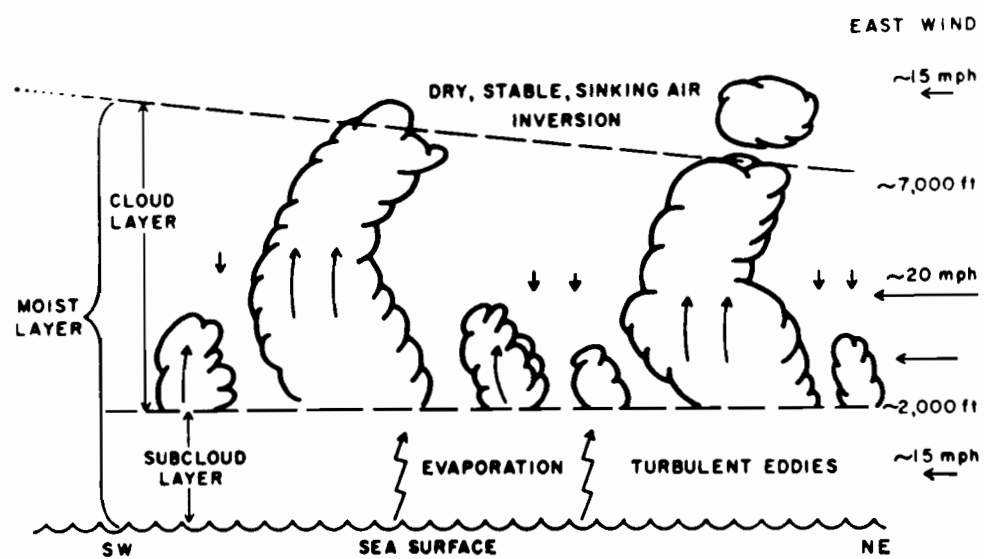


FIG. 54 SCHEMATIC VERTICAL CROSS-SECTION ALONG THE PATH OF THE TRADE WINDS

(After Malkus, 1962)

Clouds are drawn much larger than the actual scale.

FIG. 55 RAINFALL AT WATERFORD AND AVERAGE % FREQUENCY OF TRADE WIND
INVERSION OVER TRINIDAD

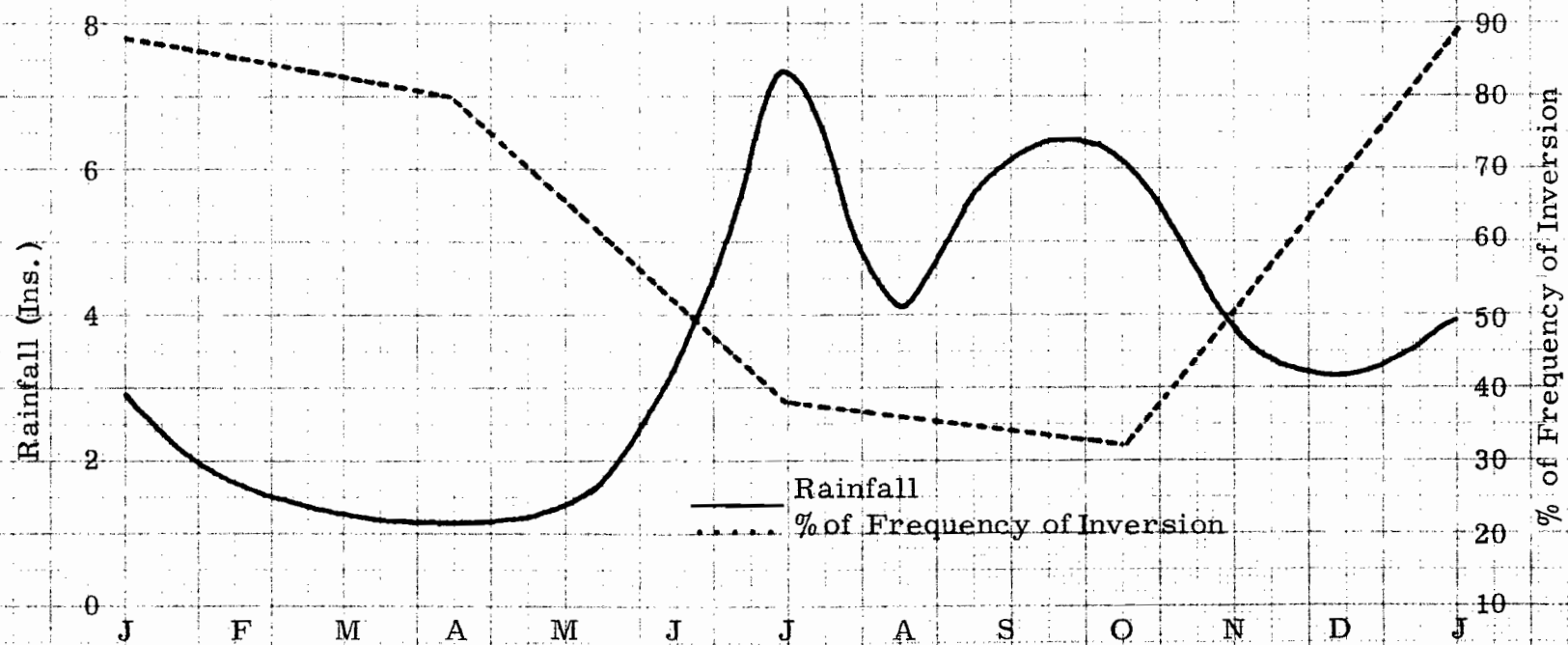


FIG. 56 AVERAGE RAINFALL AT WATERFORD AND AVERAGE STRENGTH OF TRADE WIND INVERSION OVER TRINIDAD

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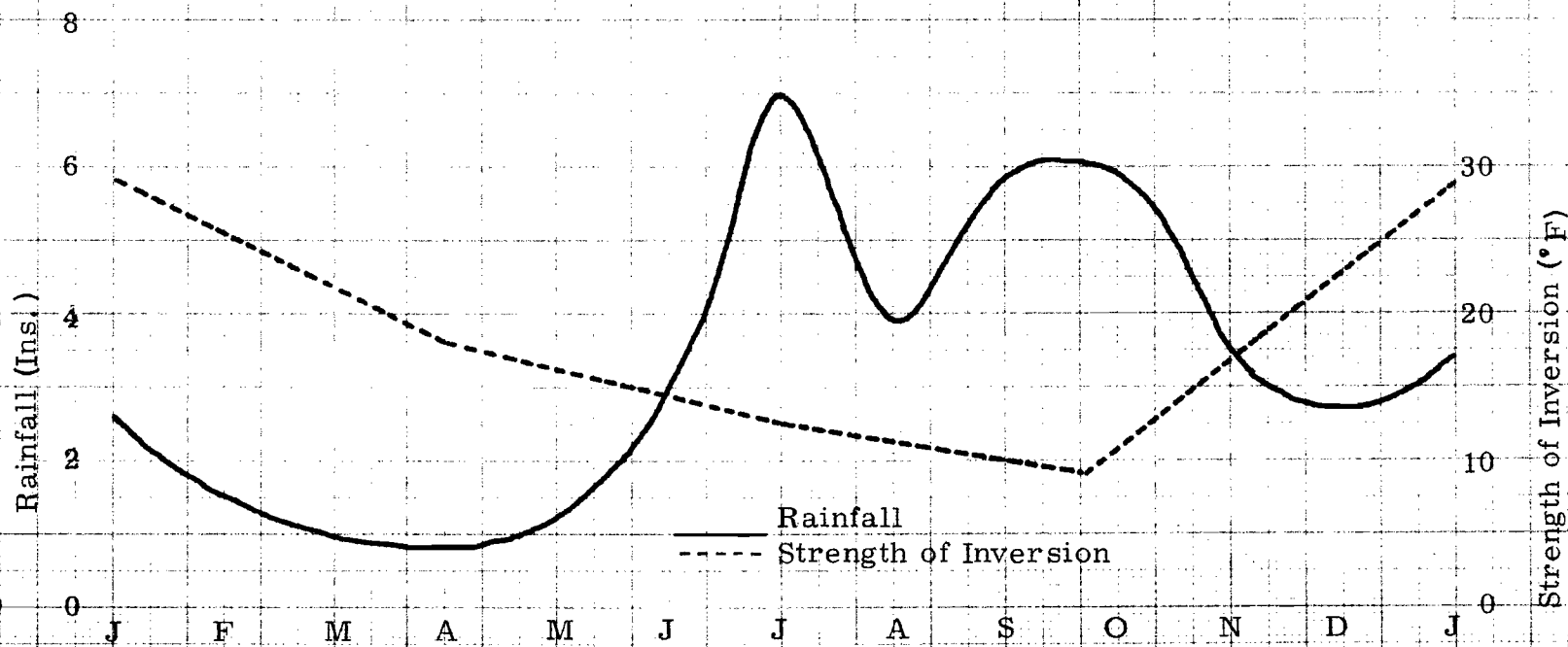
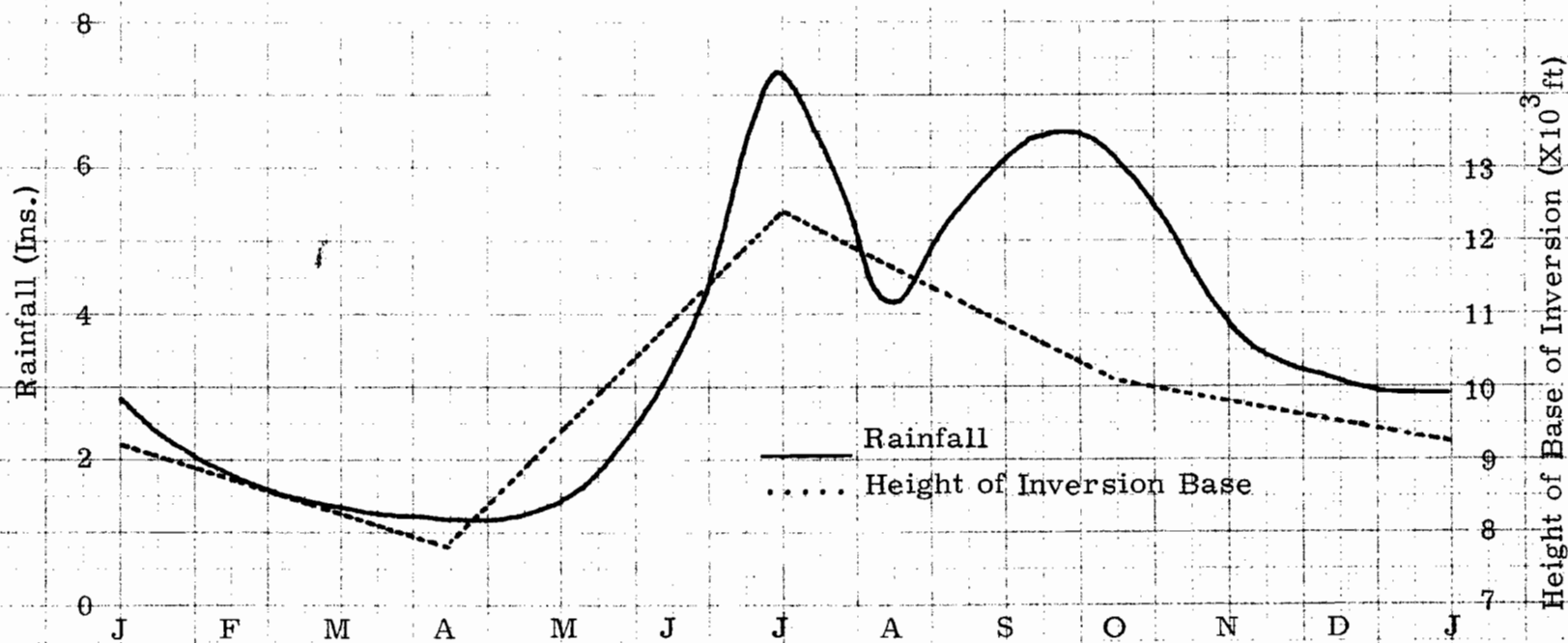


FIG. 57 AVERAGE RAINFALL AT WATERFORD AND MEAN HEIGHT (FT.) of INVERSION
BASE IN TRINIDAD

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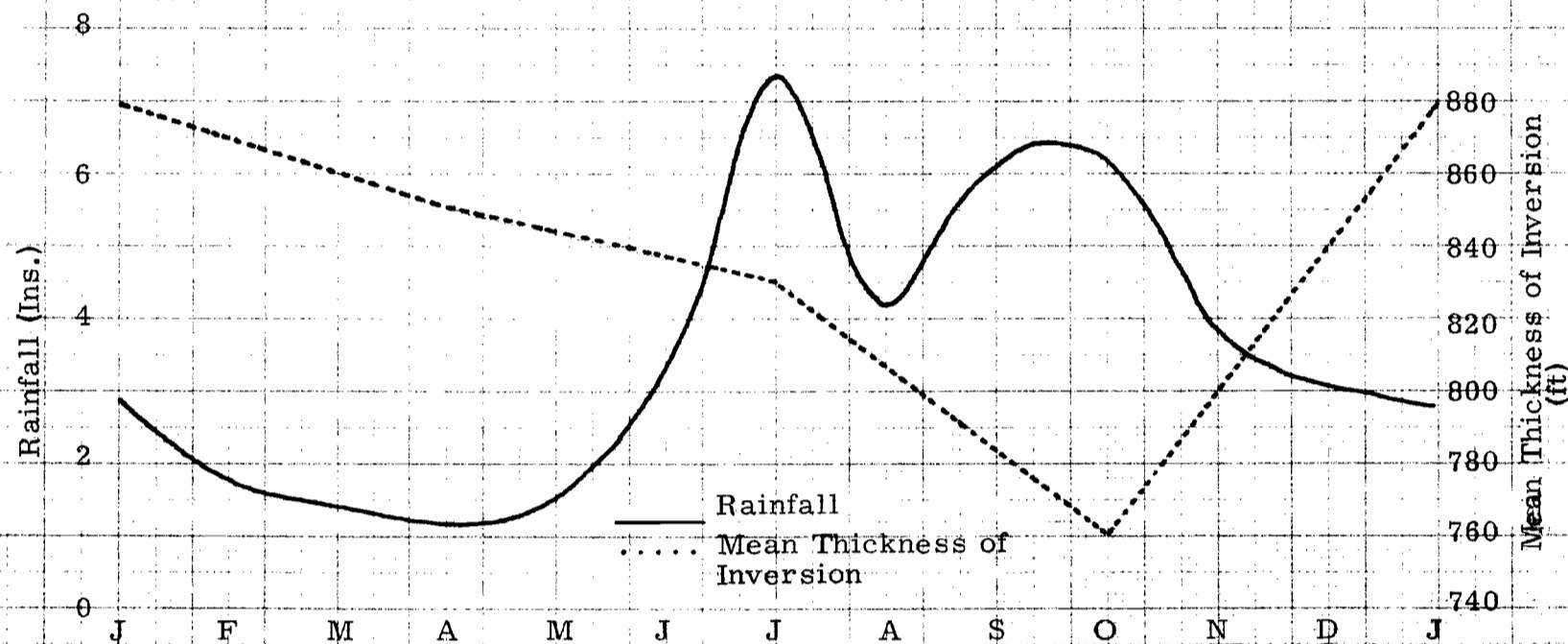
the rainy season and lowest during the dry season. Fig. 58 shows that the thickness of the inversion layer is highest during the dry season and lowest during the rainy season.

To summarize, the inversion is more frequent, stronger, lower and thicker during the dry season. All these characteristics act in the same direction to produce a strong lid to inhibit convection. During the rainy season, it is less frequent, weaker, higher and thinner. All these characteristics act in the same direction to reduce or remove completely any inhibition to convection by Trade Wind inversion. Though it may not be the sole controlling factor, the Trade Wind inversion is shown to have some amount of control on the rainfall regime. It certainly provides conditions favourable or unfavourable for cloud development and rain. It may be added that in an area of strong low level convergence the above argument does not hold. The inversion, whatever its strength and height, is lifted to great heights or even completely destroyed, giving way to development of convective clouds to great heights. (Malkus, 1962)

An objection can be raised as to whether the seasonal variations of the trade wind inversion are not the result of the rainfall regime, rather than the cause of it. This objection is answered by the way Gutnick analysed the data. He examined carefully and made sure that for all cases considered no anomalous features in the general

FIG. 58 AVERAGE RAINFALL AT WATERFORD AND MEAN THICKNESS (FT.) OF INVERSION IN TRINIDAD

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circulation pattern existed. He also excluded all other types of inversion such as radiational.

(iv) Direct thermal causes

Rainfall due to direct thermal causes in Barbados can be regarded as a diurnal perturbation of the Trade Wind regime. Differential heating of the Island sets up sea breeze which interacts with the general Trade Wind flow, producing convergence lines and cloudiness and rain. A diagram of upper air flow in relation to sea-breeze cloud is shown in Fig. 59. (after Leopold)

Skeete (1934) has observed and described in detail a type of convectional rain in Barbados called locally as "westerly rains," during the period 1924-1933. According to him, the local convectional rain is an important, though relatively infrequent type of rain. He gives the main characteristics of this type of rain as being localized, of high intensity and forming only during daytime. It is mainly confined to the months of August through November.

Though Skeete does not state that this type is the result of the interaction of the sea-breeze and the Trade Wind, it is likely that this is the case. Leopold (1949) has studied this type of convection in the Hawaiian Islands, which are also situated in the Trade Wind region. Moreover, Skeete states that according to observations, the time and location of formation of the initial convective clouds depend on the



FIG. 59 UPPER AIR FLOW IN RELATION TO SEA-BREEZE
CLOUD

(0900 hrs. - 1000 hrs.)

September 10, 1948.

(After Leopold)

direction and strength of the wind. He gives the conditions as follows:

<u>Wind speed</u>	<u>Location of initial cloud</u>
5 mph.	Inland
5-10 mph.	Over the sea and land
10 mph.	5-15 miles out to sea

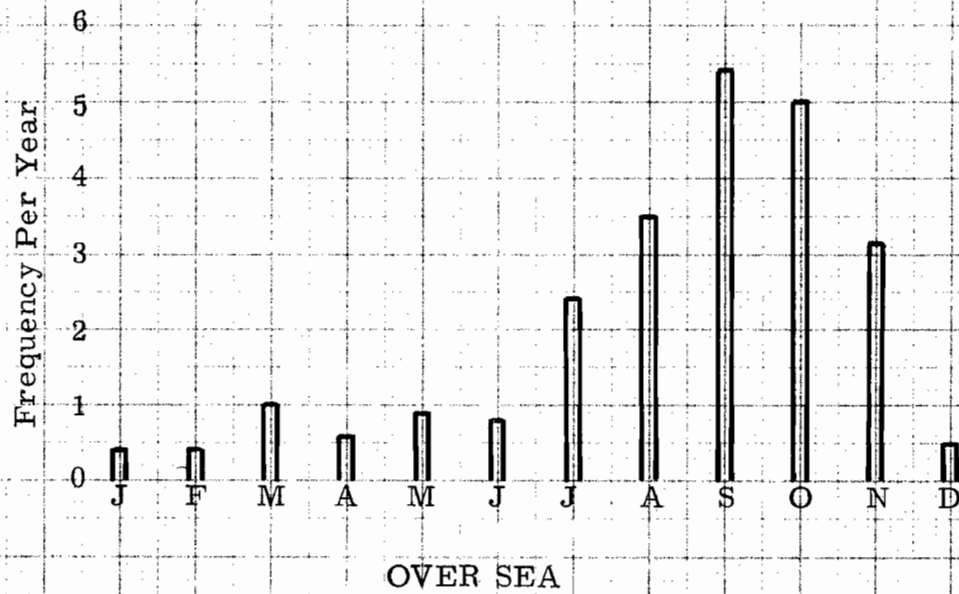
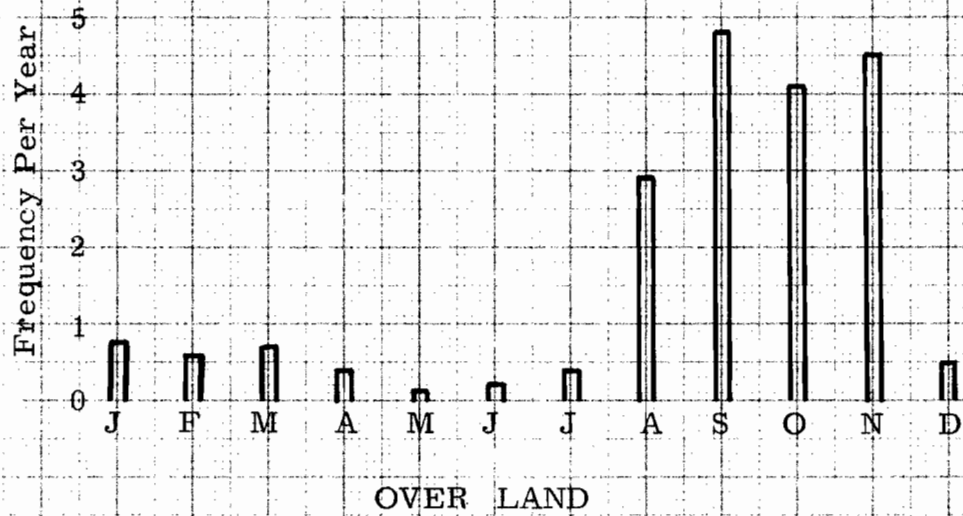
In all cases the initial development takes place opposite to the direction from which the main current is blowing. It appears that this is another way of stating the conditions under which the sea breeze reacts with the general trade wind flow inland, over the coast and over the sea (Defant, 1951). Fig. 60 shows the average frequency of convectional rain over land, and over the sea. The average number of occasions within the period August - November is about four a month, over the land and the same frequency over the sea.

It may be added that waves set up by the heated island (Malkus, 1953) similar to mountain waves may reinforce the convergence set up by the interaction of the sea-breeze and Trade Wind.

(v) Dynamical causes

Convectional rain has often been thought the most important producer of rainfall in the tropics. Hence all rainfall is attributed to thermal heating, which together with convergence of the Trades in the

FIG. 60 AVERAGE FREQUENCY OF CONVECTIONAL RAIN
BARBADOS
(1924 - 1933)



equatorial trough accentuates convection, cloudiness and rain. Hence the equatorial trough has been variously called "inter-tropical convergence zone," "inter-tropical front," etc. This is an over-estimation of the convectational rain in many parts of the tropics. Petterson says, "While scattered showers are frequent in the tropics, there has been a tendency to overestimate their importance as producers of great amounts of rain." (Petterson, 1958) Synoptic disturbances whose origin are not thermal but dynamic may contribute most of the rainfall, though their frequency may be relatively small. This may well be the case in Barbados.

Frequency of rainfall for Waterford shows that almost invariably most of the total rainfall for a month is contributed by a few number of raindays, even though the number of raindays for the month may be high. Below is a table demonstrating this point. It shows the percentage of total amount of rain, the number of raindays that contributed to it, and the total number of raindays for the month.

<u>Month</u>	<u>% of monthly total</u>	<u>No. of rain- days that contributed</u>	<u>Total no. of raindays in a month</u>
Jan. 1962	72	7	28
July 1962	53	3	24
Sep. 1962	72	6	23

Frequency analysis of rainfall for Waterford on page 70 also demonstrates this point.

Though there is no data available on the types and frequencies of such synoptic disturbances affecting Waterford, information from other sources (Riehl, 1954; Malkus, 1962; Skeete, 1934 and Dunn, 1940, etc.) confirm that the Caribbean is an important region of incidence of synoptic disturbances.

Malkus (1962) defines tropical disturbance as a region of convergence and divergence of the order of 10^{-5} sec⁻¹ with a horizontal scale ranging from 120 miles to 1,200 miles and an area averaged vertical speed of 1-50 cm/sec. It is recognizable on the synoptic map as a wave, or a closed cyclonic vortex or a shear line with a life-time ranging from two days to four weeks. These various disturbances are always recognizable as deformations in the streamline field but not always in the pressure field. They may interact or combine with each other or superpose each other in the vertical in a variety of ways.

Whatever may be their form, tropical disturbances always have the effect of altering the moist layer and therefore altering the conditions for cumulus formation.

There are no fronts within these disturbances, though many have attributed the changes that take place in the meteorological elements with the passage of these disturbances to frontal activity (Malkus, 1962; Palmer, 1951).

The disturbances that frequently affect the Caribbean and

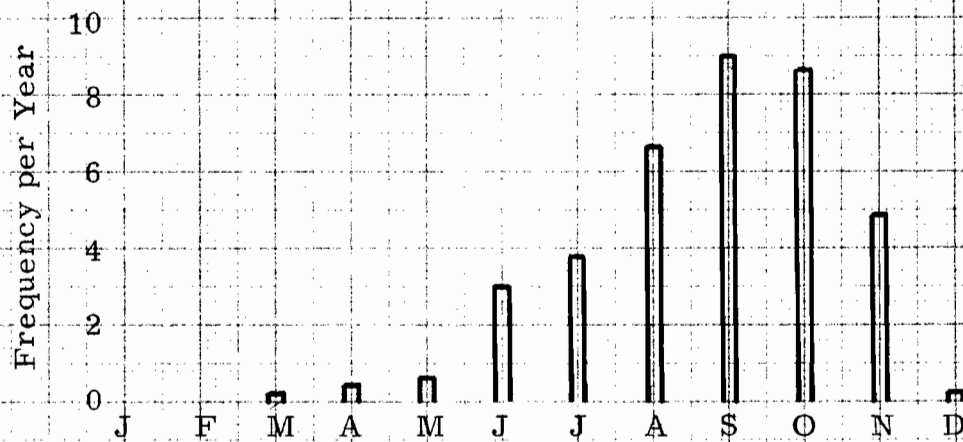
especially in the region in which Barbados lies in summer are the easterly waves and the shear lines. Fig. 63 (after Petterson) is a map showing the areas frequently affected by easterly waves.

Tropical depressions in their various stages of development also affect Barbados during the summer but their frequency may not be as high as the waves and shear lines. Its most advanced stage, namely the hurrican, is of no account in the control of the seasonal variation of rainfall regime in Barbados, in spite of its notoriety in the Caribbean. It is not a regular annual feature in Barbados. From 1870 to date, about 4-5 hurricanes have struck Barbados.

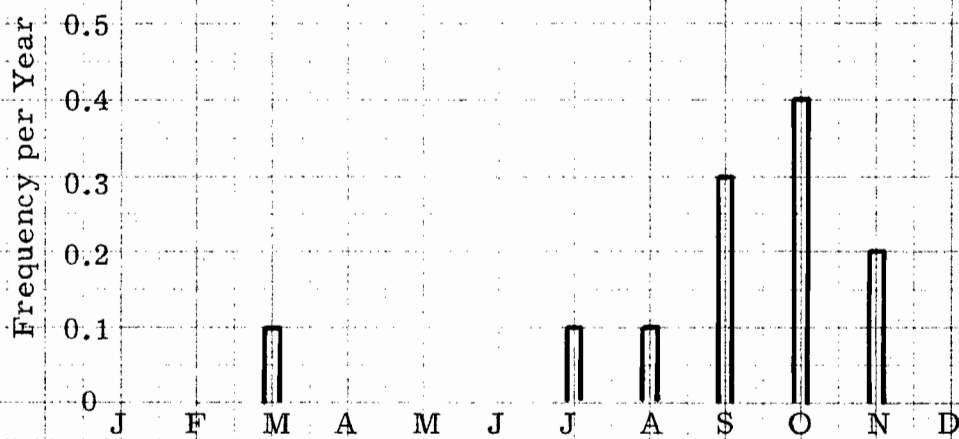
(Barbados Weather Observations Association, 1956)

The time of occurrence of these disturbances last more than the summer. Piersig (1936) gives May 28th as the earliest date on which he found lows travelling westward from Cape Verde, and November 25th as the latest date. This period fits in with the length of the rainy season in Barbados, but no conclusive statement can be made about the relative importance of the different disturbances in the absence of any detailed study of the synoptic climatology of Barbados. However, Skeete (1934) made an analysis of various types of rainfall in Barbados for the period 1924-1933 under the headings of "convectonal rains," "thunderstorms," "severe thunderstorms" and "cyclonic weather." Figs. 60-62 give their frequency of occurrence,

FIG.61 AVERAGE FREQUENCY OF THUNDERSTORMS
BARBADOS
(1924 - 1933)



MODERATE THUNDERSTORMS



SEVERE THUNDERSTORMS

FIG. 62 AVERAGE FREQUENCY OF CYCLONIC WEATHER
BARBADOS
(1924 - 1933)

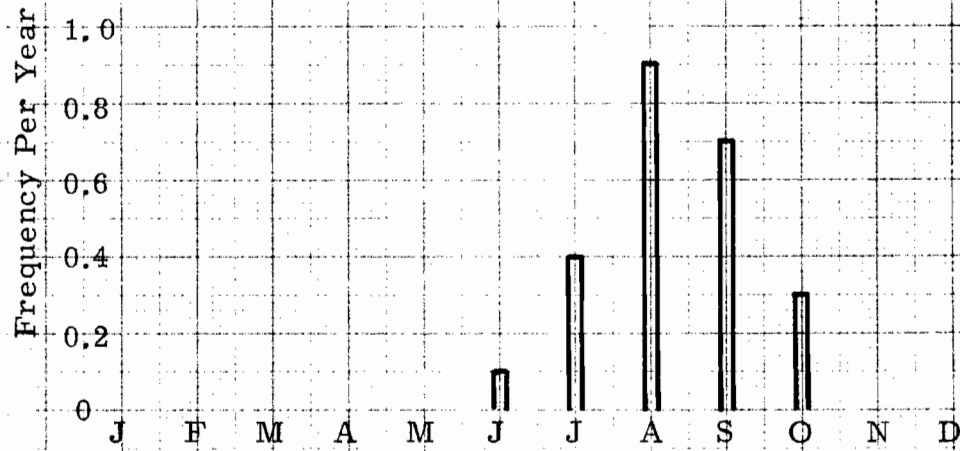
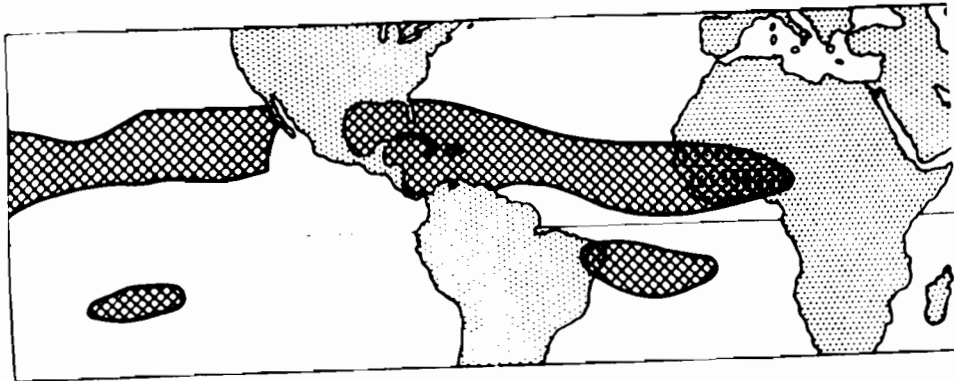


FIG. 63 MAP SHOWING REGIONS WHERE EASTERLY
 WAVES ARE FREQUENT

(After Berry, Bolley and Beers)



which have been constructed from information gathered from his paper. Most of the frequencies generally lie within June to November, which is generally the rainy season in Barbados. Still the problem of the relative importance of the various synoptic disturbances as well as the conventional rains (diurnal disturbances) in the control of the seasonal variation of rainfall is not solved. He does not show the sources of the thunderstorms; this is important because any of the disturbances can produce thunderstorms. However, his description of the severe thunderstorms suggests that they may have arisen from intense synoptic disturbances. He describes all the "cyclonic weather" as very mild or slight with only a wind shift and increase in cloudiness. This lack of detailed information on the various disturbances is understandable because the discovery of the easterly waves and the intensive study of the various synoptic disturbances started only in 1940. (Dunn, 1940; Riehl, 1940)

Disturbances of different kinds occur in the Barbados region during the winter (Riehl, 1954). Information on the occurrences of such disturbances in Barbados are not available to make any comment on their contribution to the rainfall regime of Waterford. However, from the observation of rainfall in one year (page) there is a hint that the most contributor of rainfall in the dry season may be due to such disturbances rather than convectional rains.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Summary and Conclusions

According to Köppen's climatic classification, Waterford, Barbados, has an Aw climate, i.e., a Tropical Rainy Climate with a dry period in winter. The climate therefore consists of two seasons - the rainy season and the dry season. From the standpoint of its nearness to the ocean and its small seasonal variation of temperature, Waterford's climate can also be described as oceanic.

The annual rainfall of Waterford is about 50 ins. This is representative of rainfall amounts in the lowland areas. Its annual average temperature of 79° F is also representative of temperatures in the lowland areas to the south.

The seasonal variations of the various climatic elements are typical of Tropical regions, with relatively small annual ranges. There is also very little variation from year to year of relative humidity, temperature, and surface wind speed, relative humidity being the most stable. Variability of rainfall is relatively high (16%) as compared with the variability of the other elements (1%). However, rainfall is less variable at Waterford than over the greater part of the Island. Rainfall is generally less variable in the western part of Barbados in which Waterford is situated, than in the eastern part.

The rainy season is from June to November and the dry season from December to May. About 72% of the annual total rainfall is received

during the rainy season. Temperatures are higher in the rainy season than in the dry season, while the diurnal range of temperature is lower. This fact, coupled with lower winds and higher relative humidities in the rainy season can often create low cooling power during this period, making it less comfortable than the dry season. Aperiodic variations of temperature from day to day are more during the dry season than the rainy season. The dry season is, therefore, likely to be a more favourable period for the precipitation and influence of diseases.

The prevailing wind direction is East for most part of the year with an annual frequency of about 50%. The wind blows about 90% of the time between ENE and ESE.

The persistency or steadiness of wind is high. It is about 84% for the year but can be as high as 97% during the dry season. This places Waterford in the Trade Wind region.

The analysis of five years data series for Waterford for the elements considered in this thesis appear to be sufficient for climatological purposes except for rainfall. The method of reduction has therefore been used to deduce twenty-two year average monthly, and average annual rainfall for Waterford by making use of twenty-two years rainfall data for Seawell Airport, thus making Waterford rainfall data climatologically useful.

Radiation and Evaporation data, though important, have not been analysed for lack of continuity.

Considering the climate over the whole Island, rainfall is the only climatological element that is observed throughout the Island. While temperature data is available for only five stations in Barbados, there are over fifty rainfall stations scattered evenly throughout the Island. The rainfall climate of the entire area is therefore sufficiently described. Though the temperature climate is sufficiently known in the southern parts of the lowlands, the temperature climate in the other parts is deduced by making use of the temperature data in the five stations and taking into account the topography of the Island. Wind speed measurements are also scanty and affected greatly by the exposure of the station. No definite statements can be made on the surface wind speeds over the Island except that they are expected to be high over highlands, low over lowlands; and also higher over stations with more open exposures.

It is suggested that the control of the temperature climate during the rainy season is mainly rainfall and cloudiness, while the control during the dry season is mainly the apparent movement of the sun.

Several factors are considered to have some effect on the rainfall climate. Diurnal heating and tropospheric dynamic effects, giving rise to afternoon convectional local rains and weather disturbances respect-

ively, are suggested to be the main controls of rainfall climate over the Island, the dynamic effects probably being the more important of the two.

Though the analysis in this thesis has been done with a view to providing data for various research workers in Barbados who may need climatological information, only the climatological elements that are often needed to describe climate are provided. A more specialized analysis may be required to satisfy some users of climatological information, depending on the type of investigation being undertaken.

The Chapter on Synoptic Climatology only gives suggestions of the causes of seasonal variations of temperature and rainfall climate in Barbados. It is hoped that research workers in Meteorology and Climatology, interested in Tropical weather and climate, would take up the investigations of some of the suggestions made.

APPENDIX I

ELEMENT	TYPE OF INSTRUMENT AND EXPOSURE	TIME OF READING
1. Maximum Temperature	Mercury-in-glass maximum thermometer. Exposed in standard Stevenson's screen. Dimensions of screen are 3-2/3 ft X 2 ft X 2 ft. Height of screen from ground is 4 ft.	0900 hrs.
2. Minimum Temperature	Alcohol-in-glass minimum thermometer. Exposed in standard Stevenson's screen.	0900 hrs.
3. Dry Bulb Temperature	Mercury-in-glass thermometer with dry bulb. Exposed in standard Stevenson's screen.	(0900 hrs. (1600 hrs.
4. Wet Bulb Temperature	Mercury-in-glass thermometer with moistened wick around its bulb. Exposed in standard Stevenson's screen.	(0900 hrs. (1600 hrs.
5. Soil Temperature	L-shaped mercury-in-glass thermometers sunk into grass covered soil at depths of 2", 4" and 8".	(0900 hrs. (1600 hrs.
6. Grass minimum Temperature	Alcohol-in-glass thermometer exposed 3" above grass covered soil.	0900 hrs.
7. Rainfall	Standard rainguage, 5" in diameter with rim 12" above ground which is grass covered.	0900 hrs.
8. Daily Surface Wind Run	Fritz anemometer, height 6 1/2 ft.	0900 hrs.

Appendix 1 (Continued)

ELEMENT	TYPE OF INSTRUMENT AND EXPOSURE	TIME OF READING
9. Surface wind Direction	Wind vane, height 24 ft.	(0900 hrs. (1600 hrs.
10. Relative Humidity	Derived from dry bulb and wet bulb temperatures.	
11. Duration of Sunshine*	Stokes-Campbell Tropical Pattern Recorder.	Chart changed at 1800 hrs. daily.

* Instrument installed at Codrington Agricultural Station.

Appendix 1 (Continued)

ELEMENT	LENGTH OF RECORD	CHANGES
Maximum Temperature	March 1959 - February 1964	-
Minimum Temperature	March 1959 - February 1964	Measurements by thermograph up to Dec. 1959. Minimum thermometer introduced in Jan. 1960.
Dry Bulb Temperature	0900 hrs. March 1959-February 1964. 1600 hrs. Sept. 1959-April 1964	-
Wet Bulb Temperature	March 1959 - February 1964	-
Soil Temperature	February 1960 - January 1964	-
Grass Minimum Temperature	January 1960 - December 1963	-
Rainfall	March 1959-February 1964	-
Daily Surface Wind Run	May 1960 - April 1964	(i) Anemometer height reduced from $7\frac{1}{2}$ ft. to $6\frac{1}{2}$ ft. on April 1961. (ii) Obstruction (sugar cane) on the windward side varies in height and reaches a maximum height of 20 ft. in Feb/Mar when sugar cane is harvested.
Daily Surface Wind Direction	March 1961 - February 1963	Observations stopped in April 1963 and resumed in Sept. 1964.
Sunshine Duration	March 1959 - February 1964	-

APPENDIX 2

THE DEFINITION OF TERMS

1. Annual range of temperature: The difference between average temperatures of the warmest and the coolest months.
2. Daily mean temperature : Arithmetic mean of the daily maximum temperature and the daily minimum temperature.
3. Diurnal temperature range : The difference between the daily maximum and minimum temperatures.
4. Isanormal* : A line drawn through geographical points having equal anomaly of some meteorological quantity.
5. Phase, temperature : The phase of the annual course of temperature is determined by the month with the highest and the month with the lowest temperature.
6. Prevailing wind direction : The most probable wind direction or the modal wind direction.
7. Rain day : A period of twenty-four hours, commencing at 9 am, in which at least 0.01 inch or 0.2 mm precipitation is recorded.
8. Relative temperature : The degrees by which the consecutive monthly averages exceed the average temperature of the coldest month expressed as a percentage of the annual average temperature range.
9. Relative variability : The mean deviation from the average value expressed as percentage of the average value.

Appendix 2 (Continued)

10. Resultant or mean wind^{*} : The vectorial average of all wind directions and speeds for a given level at a given place for a certain period.
11. Change, C. : A change of the sign of two consecutive deviations of the elements of a series (+ - or - +).
12. Sequence, S. : Two consecutive deviations of the same sign of the elements of a series. (++ or --).

^{*} Definition is taken from "Glossary of Meteorology" American Meteor Society, 1959.

APPENDIX 3

REDUCTION OF CLIMATOLOGICAL AVERAGES

Comparison of average values of climatic elements at different places is valid only if identical periods are considered. Because of varying lengths of climatological records from place to place a serious limitation is imposed on any attempt at spatial comparison of climatic elements.

To overcome the above limitation the method of reduction is usually employed to bring the average values of a particular element at different places to the same period. This method makes use of the quasi-constancy of differences or ratios of synchronous averages of the same climatic elements of two neighbouring stations. (Conrad and Pollak, 1962)

F. E. Dixon (1954) has shown mathematically that ratios can be used for any climatic element expressed in absolute units, but that differences can also be used only when the variations from place to place of a climatic element are small compared with the absolute values. For example, spatial variations of temperature and pressure are small compared with their absolute values, hence differences are used for ease of computation. In the case of precipitation spatial differences are not small, hence only ratios can be used.

BIBLIOGRAPHY

- Bergeron, T., "Outlines of a dynamic climatology." Met. Zeit. Vol. 47, pp. 246. (Quoted from Conrad and Pollak, 1962), 1930.
- Birkeland, B.J., and Frogner, E., "Die extreme Variabilität der Lufttemperatur," Met. Zeit., pp. 349. (Quoted from Conrad and Pollak, 1962), 1935.
- Byers, H.R., "General Meteorology." Chapter 16. McGraw-Hill Book Company, Inc., 1959.
- Colon, J., "On the heat balance of the troposphere and water body of the Caribbean Sea." National Hurricane Res. Proj. Report No. 41. U.S. Dept. of Commerce, Wash. D.C. pp. 65. (Quoted from Malkus, 1962), 1960.
- Conrad, V., "Fundamentals of Physical Climatology." pp. 27., 1941a.
- _____ "The variability of Precipitation." Monthly Weather Review. Vol. 69, No. 1, pp. 5-10., 1941b.
- _____ and Pollak, L.W., (1962): "Methods in Climatology." pp. 12, 222-242, 291-294, 296-300.
- Defant, F., "Local Winds." Compendium of Meteorology. Boston, Amer. Meteor. Soc. pp. 659. 1951.
- Dinies, E., "Luftkörper-Klimatologie; Archiv d. Deut. Seewarte." Vol. 50, No. 6, pp. 21. (Quoted from Landsberg, 1960), 1932.
- Dixon, F.E., "Climatological comparison: By differences or ratios," Bull. Am. Met. Soc. Vol. 26, pp. 293-294, 1945.
- Dunn, G.E., "Cyclogenesis in the Tropical Atlantic." Bull. Am. Meteor. Soc., Vol. 21, pp. 215. (Quoted from Richl, 1954), 1940.
- Durst, C.S., "Climate - The Synthesis of Weather." Boston, Amer. Meteor. Soc., pp. 967-975, 1951.

- Friedman, D.G., "Specifications of Temperature and Precipitation in terms of circulation patterns." J. Meteor. Am. Met. Soc. Vol. 12, pp. 428-435. 1955.
- Gorezynski, Wl., "Sur le calcul du degré du continentalisme et son application dans la climatologie," Geografisker Annaler, pp. 324. (Quoted from Conrad and Pollak, 1962), 1920.
- Gutnick, M., "Climatology of the Trade Wind Inversion in the Caribbean." Bull. Am. Met. Soc. Vol. 39, pp. 410-420. 1958.
- Haurwitz, B. and Austin, J.M., "Climatology." McGraw-Hill Book Company Inc., pp. 384. 1944.
- Jacobs, W., "Synoptic Climatology." Bull. Am. Met. Soc. Vol. 27, pp. 306-311. 1946.
- _____ "Wartime developments in applied climatology." Met. Monographs, Vol. 1. 1947.
- Koeppen, V., "Über die Abhängigkeit des Klimatischen charakters der Winde von ihrem Ursprunge." Reportorium für Meteorologie, 4(4) pp. 15. (Quoted from Conrad and Pollak, 1962), 1874.
- Landsberg, H., "Air Mass Climatology for Central Pennsylvania." Beitr.z. Geophysik Vol. 51, pp. 278-285. 1937.
- _____ "Physical Climatology." Dubois, Pennsylvania. Gray Printing Co., Inc. pp. 80-82, 131, 141-146, 147-165, 222-232. 1960.
- Leopold, L.B., "The Interaction of Trade Wind and Sea-breeze, Hawaii." J. Met., Vol. 6, pp. 312. 1949.
- McGill University, "Climatic Observations at Waterford, Barbados." Dept. of Geography, McGill University, Nos. 1 & 2.
- Malkus, J.S. and Sfeen, M.E., "The flow of a stable atmosphere over a heated Island. Pt. I." J. Meteor. Vol. 10, pp. 30-41. 1953.
- _____ "Large-scale interactions." The Sea. Vol. I. Interscience Publishers, pp. 144-151, 216-224. 1962.
- Martin, D.E. and Hawkins, H.F. Jr., "Forecasting the weather: The

relationship of temperature and precipitation over the United States to the circulation aloft." *Weatherwise*, Vol. 3., pp. 16-19, 40-43, 65-67, 89-92, 113-116, 138-141. 1950.

Middleton, W.E.K., and Spilhuas, A.F., "Meteorological Instruments." University of Toronto. pp.127. 1953.

Petterson, S., "Introduction to Meteorology." McGraw-Hill Book Company, Inc., p.241. 1958.

Piersig, W., "Aus dem Archiv der deutschen Seewarte, Vol. 54., No. 6. (Quoted from Riehl, 1954) 1936.

Riehl, H., "Tropical Meteorology." McGraw-Hill Book Company, Inc. Chapters 1, 2, 9, 10. 1954.

Rouse, W.R., "The moisture balance of Barbados and its effects on Sugar Cane yield," M.Sc. Thesis. McGill University. pp. 1-4, 13, 24, 35. 1962.

Skeete, C.C., "Weather Observations and Records in Barbados, 1924-1933." *Journal Barbados Museum and Hist. Soc.* Vol. I, No. 3, pp. 1-20. 1934.

_____, "Hurricanes." *Journal Barbados Museum and Hist. Soc.* Vol. 18, Nos. 1 & 2. pp. 39-43. 1951.

Walker, E.R., "A Synoptic Climatology of British Columbia." Ph.D. Thesis, McGill University, pp.12. 1961.

Weather Observations Association, Barbados: "Hurricane 'Janet' at Barbados." 1956.