Reprinted from METEOROLOGICAL MONOGRAPHS, Vol. 1, No. 3, June, 1951, pp. 24–33
Printed in U. S. A.

ON THE RAINFALL OF HAWAII:

a group of contributions

by

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THE GEOGRAPHIC DISTRIBUTION OF AVERAGE MONTHLY RAINFALL, HAWAII*

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(Original manuscript received 25 October 1948: revised manuscript received 31 July 1950)

ABSTRACT

Extreme geographic variations in rainfall in Hawaii pose a problem of finding a simple parameter of rainfall which will be descriptive of both rainfall amounts and distribution. With a view to developing such a parameter, regression formulae are developed which relate mean monthly rainfall to mean annual rainfall. Mean monthly rainfall is shown to be the result of two independent factors, general rainfall and orographic rainfall. Each of these two rainfall types has individual annual march curves. The integrated result of these distinctive variations through the year is the observed mean annual rainfall pattern. Having separated the annual march curves of the general rain and orographic rain, the local geographic rainfall distribution patterns appear much more simple and logical than had been previously realized.

The method used provides a technique for relating rainfall in wet areas to that of dry areas and appears to lend itself to the description of rainfall distribution and amounts which would be useful in rainfall forecast problems.

1. Introduction

A striking feature of the rainfall picture in the Hawaiian Islands is the extreme variation in geographical distribution. One of the world's wettest spots is located on a mountain top not more than twenty miles from a semi-arid coastal plan. In addition to great differences geographically there are important month-to-month variations. The real nature of these extreme variations in geographic distribution has not been discussed in the literature. It is known that orographic factors give rise to steep gradients of rainfall in the mountainous areas. The maximum rainfall occurs slightly to the lee of mountain crests. But no studies have attempted to explain in detail how the large observed geographic variations come about. The general rules governing relative importance of orographic rain and general storm rainfall have been obscured by great differences between islands and portions of islands.

The possibility of quantitative rainfall forecasts to serve the agricultural, industrial and other interests in the islands hinges on a solution of the problem posed by these extreme variations. Simple parameters must be found which will adequately describe them. Rainfall data are collected from 875 rain gages operated in the 6400 square miles of the Territory and this large volume of data must be related in some manner which will permit forecasts of a few parameters to describe adequately the large differences between the different gages.

2. Rainfall parameters

In 1948 Halstead and Leopold [2] prepared a series of monthly median rainfall maps for the Island of Oahu. An eleven-year period of record was used for

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* Published with the approval of the Director as Technical Paper No. 173 of the Pineapple Research Institute of Hawaii.

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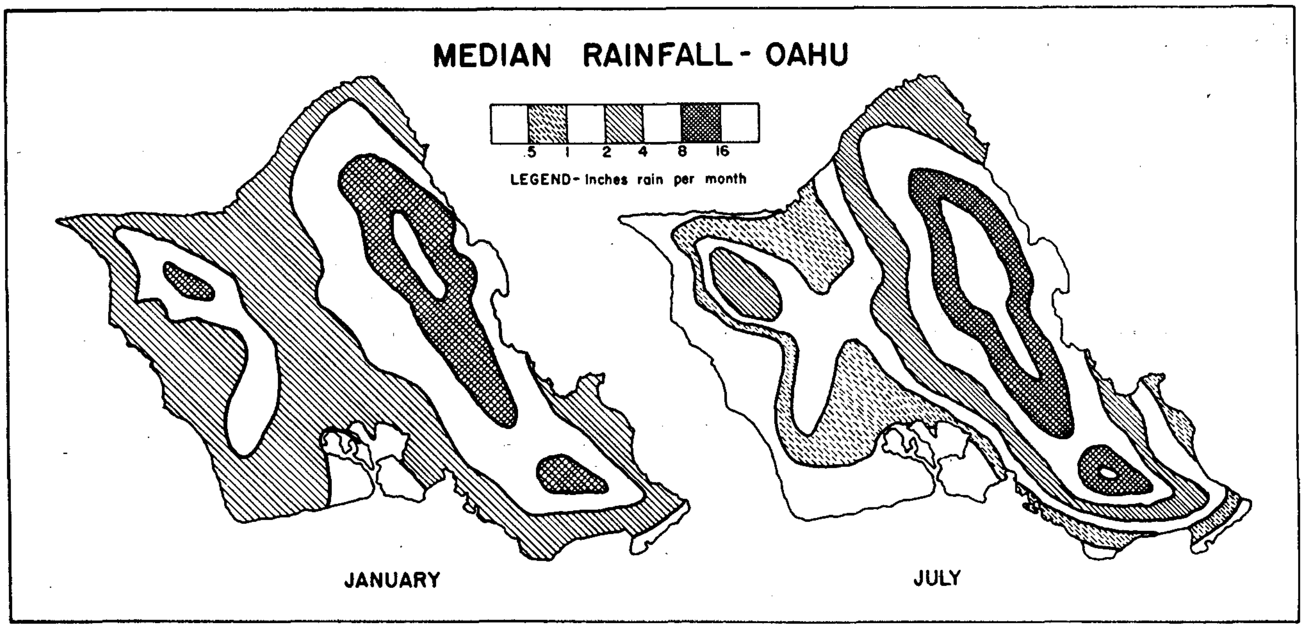

FIG. 1. Median rainfall on Oahu, Territory of Hawaii, for January and July.

each of 131 stations. This network averaged one station for each 4.6 square miles of the island. Fig. 1 presents a simplified version of the January and July isohyetal maps from the above publication. While the magnitude and spacing of the isohyets change from month to month, the shapes and positions of the areas enclosed remain similar. Each month's pattern bears a close resemblance to every other month's pattern and to the mean annual pattern, as shown by the isohyetal map included in the introduction to this monograph.

On the basis of existing concepts of rainfall distribution in the Islands, one would expect a series of monthly charts to vary in pattern from season to season. For instance, if it is presumed that rainfall is heavier on the windward slopes of an island, it might be expected that the center of maximum rainfall would be displaced farther to windward during the periods of strong, steady, easterly flow in the summer. The original purpose of the Halstead-Leopold series was to define such differences as these in quantitative terms and to split the island into several homogeneous areas which would behave as units within themselves under varying meteorological conditions.

Suffice to say that no such breakdown was ever accomplished. The similarity in isohyetal pattern between the winter and summer months was so great that no conclusions could be drawn from even a careful analysis of the slight differences. This can be visually checked by glancing at the maps of fig. 1 and forgetting for the moment the actual values of the isohyetal lines. The shapes and positions of the areas enclosed in the isohyetal lines are similar.

If, when two rainfall maps are compared, the shapes of isohyetal patterns are similar but there is variability in the values and spacing of the isohyets, then it might be possible that the whole map could be described by these two variables. The two variables may be plotted against one another in an attempt to delineate the

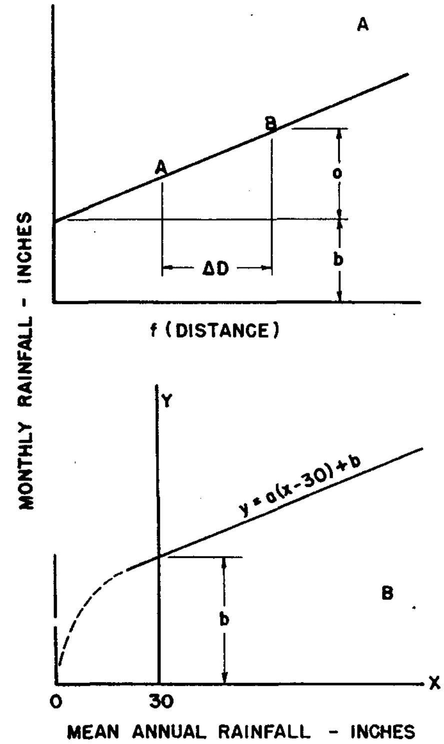

FIG. 2. (a) Schematic representation of an isohyetal map in the form of a cross section perpendicular to the isohyets; and (b) schematic representation of relation of annual to monthly rainfall.

characteristics of the individual map. If the graphs thus derived show some consistent relation between stations in an individual month, and two months are shown to be distinctly different, the usefulness of the variables chosen is established.

In order to obtain values for the two variables, isohyetal magnitude and isohyetal spacing, let us examine the isohyetal map in the diagramatic form of fig. 2a. This represents a cross section through the monthly isohyetal map with rainfall plotted against a function of distance. Let A and B represent any two stations separated by a small geographic distance ΔD. Uniform spacing of isohyets in this distance ΔD would be indicated by linear increase of rainfall from A to B. It is clear that the rain at each station could be expressed as the sum of two quantities: (1) a uniform blanket of rain over the whole island and the open ocean equal to depth b; (2) an increment of rain representing the orographic effect, o, which differs from station to station as a function of the gradient or isohyetal spacing.

The measurement of the gradient of rainfall through distance is the next problem. In order that the diagram of fig. 2 fit the general case and describe the relation between all stations, the parameter plotted along the abscissa must be a function of distance. However, it

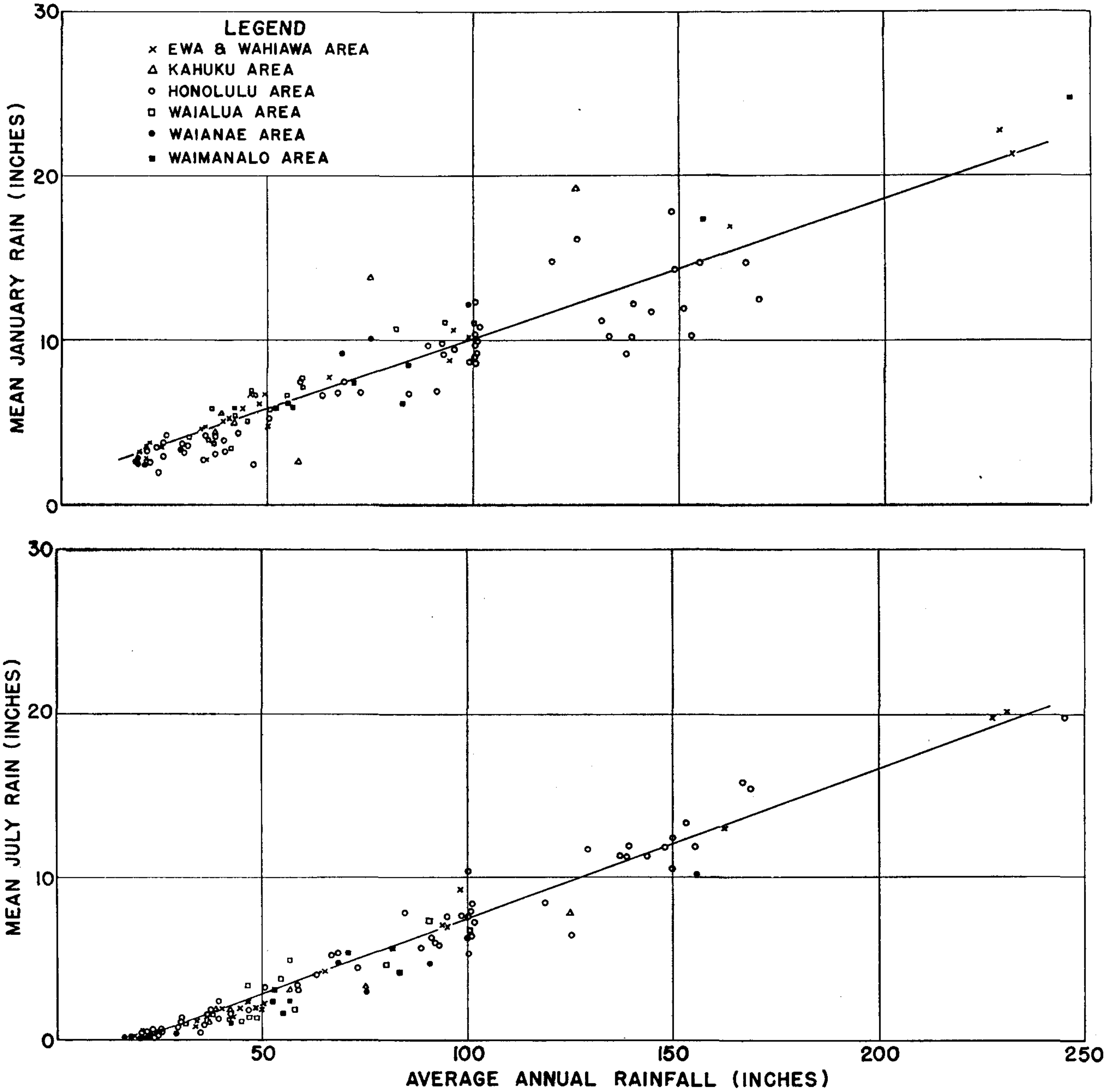

FIG. 3. Scatter diagrams of mean monthly rainfall versus mean annual rainfall for all available Oahu stations.

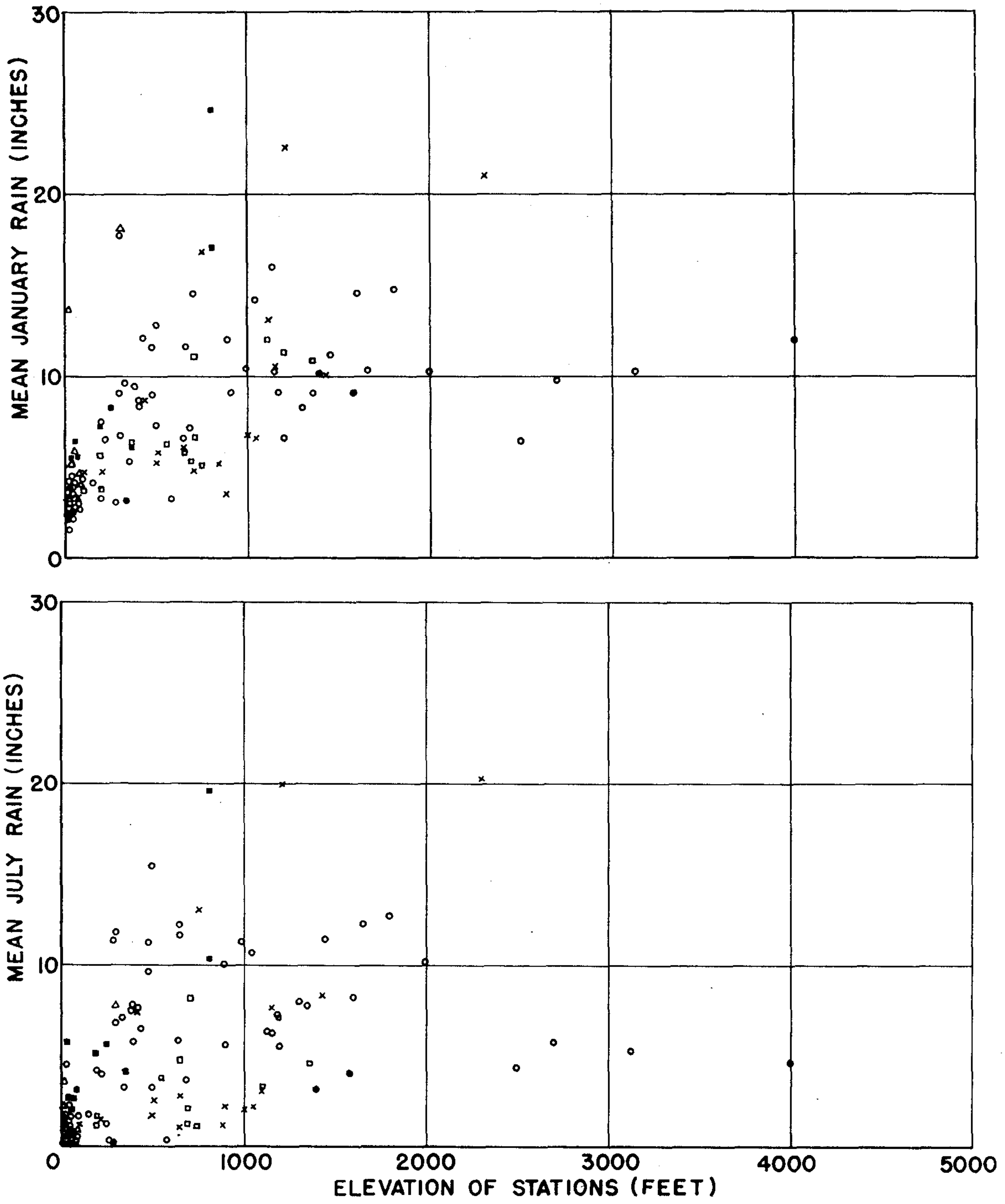

Fig. 4. Scatter diagrams of mean monthly rainfall versus station elevation for all available Oahu stations.

should be of such character that when any two stations are plotted in their proper relation along the abscissa, their mean monthly rainfall, ordinate value, will fit the same line *A–B*. Three possible functions of distance would be: (1) distance itself, in miles; (2) elevation; (3) mean annual rainfall. Inspection of the isohyetal maps immediately indicates that the gradient of rainfall through distances measured geographically in miles is not constant because of steep gradients in the mountains and flat gradients over the plains.

To test elevation and mean annual rainfall as possible abscissa parameters, small sample areas were outlined on one of the isohyetal maps of monthly rain. The gradient of monthly isohyets corresponded closely with the gradient of mean annual rainfall in each of the sample areas examined, but not with the gradient of elevation. Therefore, mean annual rainfall was chosen as the abscissa. The graph as finally used is shown diagrammatically in fig. 2b.

When average annual rainfall equals zero ($x = 0$), there can be no monthly rainfall, and therefore the graph must go through the origin as indicated by the dotted portion of the curve in fig. 2b. Plotting monthly against annual rainfall for Hawaiian stations, however, over the range of observed values of annual rainfall the relation is essentially linear. The linearity is indicated by the sample graphs in fig. 3, where mean January and mean July rainfalls are plotted against mean annual rainfall for Oahu stations.

To simplify the description of the relationship we will, therefore, treat the graph as a linear function of the form $y = ax + b$ for all portions of the graph defined by Hawaiian stations. The minimum annual value of rainfall at any station in the Territory is about 12 in. We will measure the intercept "b," not at $x = 0$, but at $x = 30$ in., which is considered to be the mean annual rainfall over the open ocean in the locality.

Inspecting this graph, $y = a(x - 30) + b$, we see that

y = the mean monthly rainfall at a station;
x = mean annual rainfall at the station;
a = the gradient factor or observed orographic increase of rainfall through an increment of average annual rainfall;
b = a geographically constant quantity derived from a rainfall blanket of uniform thickness over the whole island and adjacent open sea.

If the average annual rain at a given station is known, its January or July mean rain can be approximated from fig. 3 by reading off the coordinates of the line drawn to represent the individual points.

Fig. 4, on the other hand, shows that mean monthly rain plotted against elevation does not give a consistent relation between stations. Therefore, elevation would not be satisfactory as the abscissa parameter.

Three questions now come to mind in consideration of fig. 3. (1) How large is the scatter of individual stations about the mean lines drawn to represent them? (2) How do the mean lines compare from month to month? (3) How do mean lines for different islands compare? These questions will now be discussed.

3. Relation of individual areas to the island as a whole

In the preparation of fig. 3, stations in various portions of the island were designated by different plotting symbols. It is immediately apparent that stations in a given geographic area may have a large spread in mean annual rainfall. On the other hand, a single line drawn to represent the island as a whole represents moderately well each individual portion of the island. That one line seems to represent all areas of an island in a given month is typified by the two months shown in fig. 3, and the same fact seemed true for the remaining months of the year. This will now be subjected to a statistical test.

The division of an island like Oahu which should most probably show a difference in the regression of annual against monthly rainfall would be a split into windward and leeward areas. Oahu has a long mountain range perpendicular to the trade winds and the orographic rain related to this range is one of the characteristic features of the rainfall.

Five sample stations were selected to represent windward and five to represent leeward conditions on Oahu. They were chosen to provide in each district a considerable range in mean annual rainfall. They are listed below:

SELECTED RAIN GAGES—OAHU

Windward			Leeward		
Name	Elev. (ft)	Mean annual rainfall (in.)	Name	Elev. (ft)	Mean annual rainfall (in.)
Kahuku	20	37	Waianae Valley	40	18
Kaneohe NAS	200	57	Ewa	40	21
Punaluu	40	71	Waianae Mauka	1500	68
Waiahole	750	155	Tantalus	1400	100
Kahana	800	245	Manoa HSPA	500	170

For two months, February and April, the rainfall totals were tabulated for each of five years, 1944–48 inclusive. The individual monthly totals were paired with the annual totals for the respective years providing 25 pairs of values for windward and 25 for leeward for each of two months. These were analyzed by covariance techniques to determine differences between windward and leeward locations. The results are shown below.

COMPARISON OF WINDWARD VS. LEEWARD—
OAHU—FEBRUARY

Test of significance between adjusted mean values of monthly rain:

	Deg. free.	Sums sq.	Mean sq.
Total	48	611.40	
Ave. within windward-leeward	47	573.92	12.2
Between adjust. means	1	37.48	37.5

F = 3.07 (not signif.)

Test of significance between regression coefficients:

	Deg. free.	Sums sq.	Mean sq.
Ave. within windward-leeward	47	573.92	
Deviation from indiv. regressions	46	573.39	12.5
Between regression coefficient	1	0.53	0.5

F = 0.04 (not signif.)

Comparing windward versus leeward for Oahu in April, F = 0.92 (not signif.) between adjusted means, and F = 0.36 (not signif.) between regression coefficients.

These tests show that for the sample studied, there was no significant difference between either the adjusted mean values of monthly rainfalls of windward

TABLE 1. Slopes and intercepts of lines relating mean monthly rainfall to mean annual rainfall
Slope: Inches of mean monthly rainfall per inch of annual rain.
Intercept: Inches of monthly rain at annual rainfall of 30 in.

	KAUAI		OAHU		MAUI		WINDWARD HAWAII		MEAN	
	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
January	0.096	4.0	0.093	3.5	0.074	4.0	0.093	3.0	0.089	3.6
February	.062	2.7	.074	4.4	.076	3.9	.069	3.2	.070	3.6
March	.091	3.9	.079	3.4	.084	3.1	.091	5.2	.086	3.9
April	.099	1.6	.101	3.1	.117	2.8	.093	2.7	.103	2.3
May	.091	1.3	.081	1.5	.081	1.3	.086	1.1	.085	1.3
June	.069	1.5	.081	1.2	.072	0.9	.065	0.4	.072	1.0
July	.091	1.2	.091	1.1	.091	1.0	.091	0.7	.091	1.0
August	.091	1.5	.096	1.4	.091	1.2	.106	1.1	.096	1.3
September	.094	1.7	.091	1.7	.074	1.4	.079	1.4	.084	1.6
October	.074	2.3	.074	2.0	.067	1.6	.060	2.3	.069	2.0
November	.093	3.1	.091	3.6	.099	1.0	.091	3.4	.094	2.8
December	.091	4.0	.089	4.5	.089	4.5	.093	3.5	.090	4.1

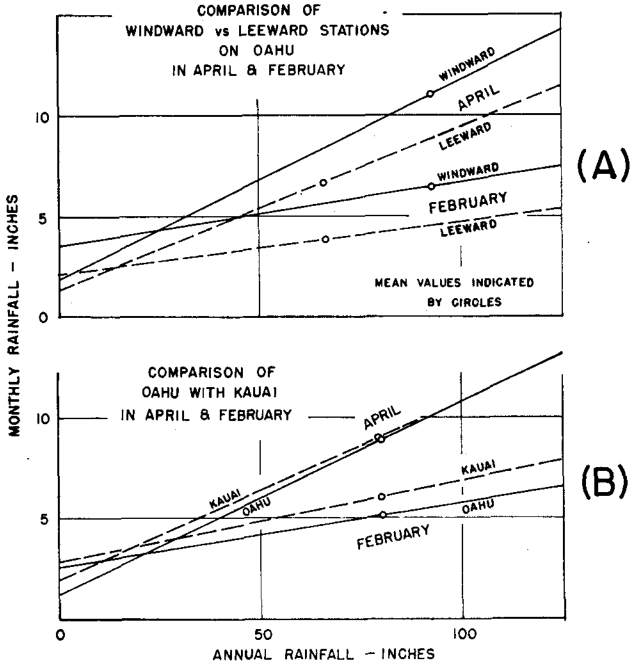

FIG. 5. Least square lines relating monthly to annual rainfall for selected months and islands.

and leeward nor between the slopes of the lines (regression coefficients). This can be visualized better by inspection of fig. 5a which shows the least square lines of the regression.

4. Month-to-month and island-to-island comparisons

By plotting mean monthly against mean annual rainfall values for all stations on each island, mean relations were determined. The lines are described in table 1 by their slopes and their intercepts at annual rainfall equal to 30 in.

Inspection of the slopes and intercepts for the mean months indicates that strong differences occur between months, both in slopes and intercepts, but only small differences between islands. To test for significance, we again used the individual monthly values and the corresponding annual values at selected stations. The same stations, months, and years listed previously for Oahu were compared with Kauai stations for the same period. To represent Kauai thirteen stations were chosen:

SAMPLE STATIONS ON KAUAI

Name	Elev. (ft)	Mean annua rainfall (in.)
Waiawa	38	19
Kukuiula	78	37
Kealia	11	40
Anahola	20	50
Homestead	712	51
Hanamaulu	175	57
Princeville Plant.	400	89
Koloko Reserv.	730	90
Papuaa	538	101
Waiahi Lower	550	117
Iliiliula Intake	1070	161
Halenanaho	490	162
Intake Wainiha	700	176

February and April were the months chosen for test. Using five years (1944–48), there were 65 pairs of values for each month on Kauai and 50 pairs for each month on Oahu. Inspection of the annual march curves for slope and intercept, fig. 6, shows that these months are representative of the differences between peaks and troughs of the annual march of slope. February and April, moreover, are in the same season but separated far enough to remove persistence. The results of the comparisons by covariance techniques are shown below:

Comparing:	Significance of difference between adjusted mean values of monthly rain	Significance of difference between regression coefficients
February vs. April		
On Oahu	F = 11.8**	F = 15.3**
On Kauai	F = 7.2**	F = 5.6*
Oahu vs. Kauai		
In February	F = 1.7 n.s.	F = 0.2 n.s.
In April	F = 0.02 n.s.	F = 0.09 n.s.

** Significant to 1 per cent; * significant to 5 per cent; n.s.—not significant.

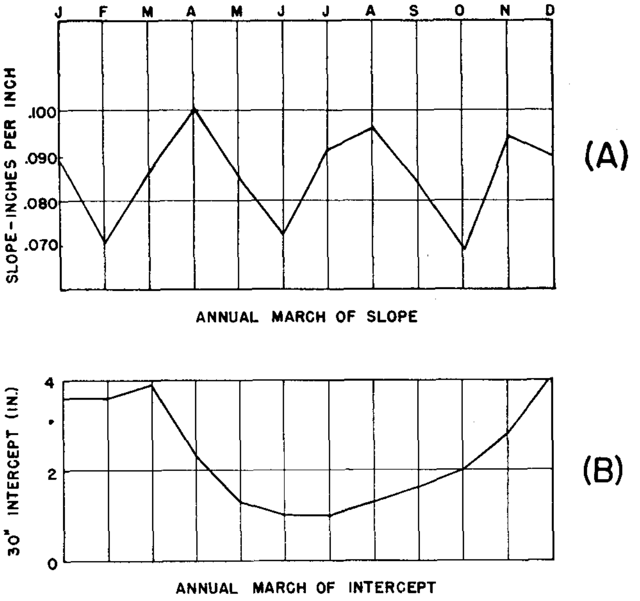

FIG. 6. Seasonal variation in slope (orographic component) and thirty-inch intercept (cyclonic component) of Hawaiian rainfall.

The statistical analysis of the sample indicates that the differences noted by inspection of table 1 are real, that is, that both slopes and intercepts are significantly different between months but are not significant between islands in the same month. Fig. 5b provides a graphical picture of the statistical data, showing the lines of best fit as computed in the statistical analysis.

It has been shown that for practical purposes we can treat the Territory as a whole in the relation of monthly to annual rainfall. Each mean month can then be represented by one line on the graph of mean annual versus mean monthly rainfall. The lack of difference between windward and leeward rainfall patterns was, of course, initially observed on inspection of the Halstead-Leopold isohyetal maps, and was one of the considerations prompting the present study.

The physical explanation of this lack of discrepancy between windward and leeward responses to varying meteorological conditions is partially to be found in the increasing steepness of the isohyetal gradients in the direction of maximum rainfall values. As we approach the center of maximum rainfall along an isohyetal gradient, the rainfall increases at a logarithmic rate as indicated by studies of the authors and by Landsberg [4], Wentworth [10] and others. The extremely sharp maxima that result from the logarithmic progression indicate that these centers must serve as focal points for rainfall activity and that orographic rainfall must almost invariably have its inception and maintain its strongest activity at these points regardless of wind direction and other synoptic considerations.

This reasoning might be expected to break down in the case of mountains which are high enough and broad enough to completely block the normal flow of the lower level winds. Mauna Loa and Muana Kea on the big island of Hawaii may constitute such a barrier and slopes and intercepts from the Kona area of leeward Hawaii do not fit the general pattern as well as those from other areas. For this reason, the Kona area was omitted in establishing the seasonal variation curves for the Territory (table 1).

5. Cyclonic versus orographic rainfall

We can now proceed to a physical explanation of the relation of mean monthly to mean annual rainfall. Over the open ocean the mean annual rainfall has no appreciable horizontal gradient in an area as small as that represented by the area of one of the Hawaiian Islands. Rainfall variations due to orographic lifting and to sea-land convective activity are absent.

This reasoning leads to the conclusion that the steep gradients of rainfall with respect to distance observed in Hawaii are primarily caused by local features, the most important of which is topography.

It is apparent, then, that the total rainfall at an island station is in most cases composed of two components. One of these is a geographically constant amount supplied by general and widespread cyclonic disturbances. In the absence of orographic activity, this cyclonic component would provide a uniformly thick blanket of rainfall at all gages. Orographic activity, on the other hand, works in such a fashion as to supply varying amounts of rainfall at different stations. It may operate in the absence of cyclonic activity or in combination with it. In the latter case, the orographic effect may actually be a negative one, depriving certain stations of some of the rainfall which the cyclonic activity would otherwise have provided.

Referring once more to the general equation for the regression lines, $y = a(x - 30) + b$, it has been stated that the constant a, which defines the slope of a regression line, is a measure of the orographic activity. In terms of an isohyetal map it can be defined as the relative gradient of the isohyets, relative, that is, with respect to the gradient of the mean annual isohyetal map. It can be measured on a monthly isohyetal map by dividing the observed gradient between a point A and a point B by the gradient between point A and point B on the mean annual isohyetal map.

It is not possible to determine the amount of the cyclonic component of rainfall from the equation $y = a(x - 30) + b$ alone. However, if the mean annual total of cyclonic rainfall were known, the monthly amounts could be obtained from the equation

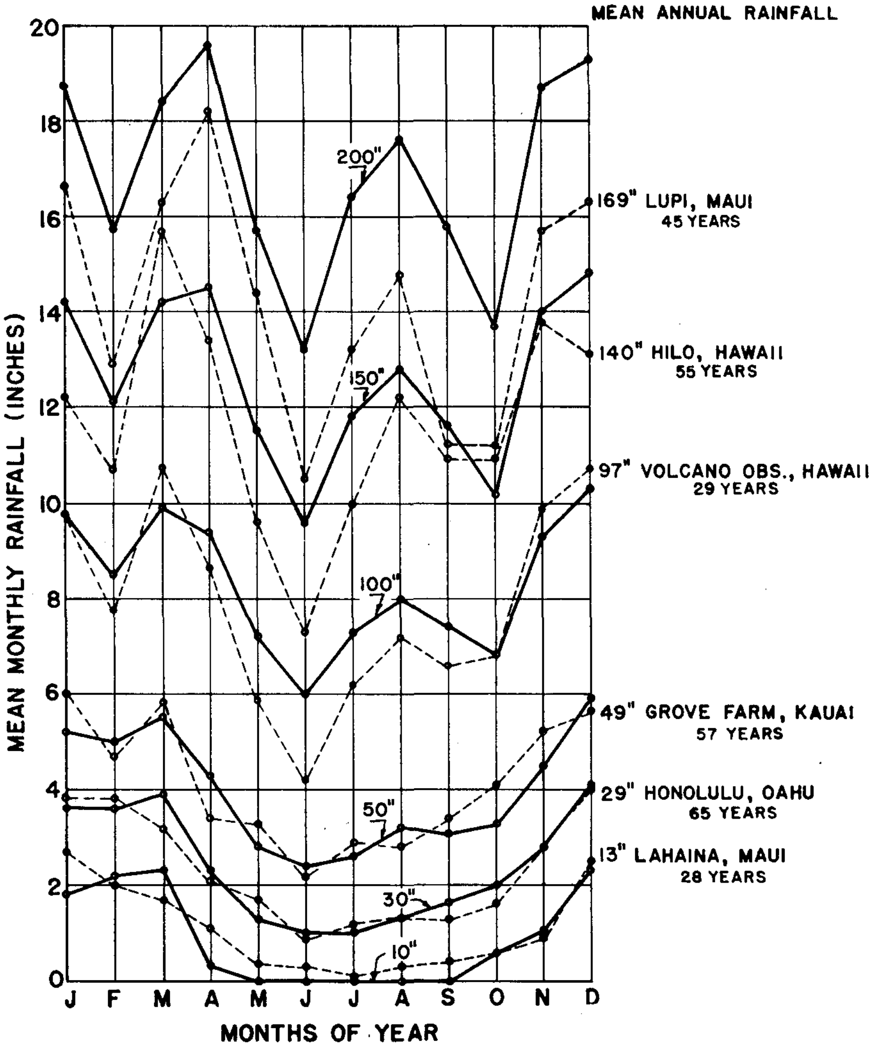

FIG. 7. A family of curves (solid lines) which show the seasonal variation of rainfall at progressively wetter hypothetical stations. Labels on curves are mean annual rainfall. Dashed lines are observed seasonal variations in rainfall at several Hawaii stations with long periods of record.

by measuring them where the monthly regression lines crossed the ordinate having the known mean annual value.

We have measured the intercept of the line on the graph at an annual rainfall of 30 in., the approximate annual rainfall over the ocean estimated by reference to global isohyetal maps of Conrad [1] and Haurwitz and Austin [3]. The annual march of the thirty-inch intercept, then, should be the annual march of rainfall at stations not influenced by orography or of rainfall over the open ocean. If this is true, the annual march of the measured intercepts should express the annual march of rainfall from general storms. We know that general storms have a winter maximum and summer minimum, and vary more or less smoothly in frequency during the intervening months. The annual march of thirty-inch intercepts from the data as compiled from the present study is shown in fig. 6b. The progression during the year fits very nicely the conclusions deduced above. This graph bears a close resemblance to one defined by Riehl [5] as the "Seasonal Variation of Rainfall Due to Storms".

Similarly, we may now construct the annual march of slopes, or the orographic factor, plotted in fig. 6a. Comparison of this graph with that of the cyclonic factor in fig. 6b shows the independent behavior of the two variables. Although no physical explanation is at hand to account for the three rather uniform cycles per year displayed by this variable, the variation with sharp minima in February, June, and October appears to be very real. The curves for each island considered separately show approximately the same changes. Evidence is on hand which links this orographic factor to stability. Mordy* has shown that a similar annual

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* Mordy, W. A., unpublished data.

march is found in the height of the trade wind inversion above Honolulu, and in the lapse rate below the inversion. The seasonal variation of surface wind speed, based on fourteen years' data at Pearl Harbor [9], also shows minima in February, June, and October, although the three phases are not as uniform as those of the variation in slope.

The annual march of slope, fig. 6a, closely resembles a figure given by Solot [7] demonstrating the annual march of rainfall for windward stations. The similarity is to be expected because windward slopes of moderate to high rainfall receive the bulk of their rainfall as a result of orographic lifting.

The cyclonic rainfall, being an additive quantity, has relatively small influence in the seasonal variation of rainfall at the wet mountain stations, and the wetter a station, the more closely its seasonal variation curve resembles that of the orographic factor. This is shown graphically in fig. 7. The family of solid line curves in fig. 7 represents seasonal variations in rainfall at hypothetical and progressively wetter stations. These were obtained directly from the average slopes and intercepts in table 1. The dotted lines represent the actual seasonal variation at several well-known stations with long rainfall records. It can be seen that the hypothetical curves account for the major fluctuations in the curves of real stations.

Fig. 7 demonstrates the importance of the orographic cycle in its contribution to rainfall in the watershed areas and indicates a relationship between the annual cycles for wet stations such as Hilo and dry stations such as Honolulu. Honolulu's wet-winter dry-summer type of annual cycle has formerly been regarded as the "normal cycle" for this area, but fig. 7 shows that it represents only one stage in a graduated series of cycle patterns which range from the almost purely cyclonic type of the dry zones to the orographic type of the wet zones.

Annual march curves of the type shown in fig. 7 were studied intensively by Tüllman [8]. He compared curves from a very large number of Pacific Island stations including nearly all the published stations from the Territory of Hawaii. From an examination of Tüllman's data, it appears that the extreme geographic variations in rainfall observed in Hawaii are not found in most other Pacific Islands. This is largely due to the fact that the cyclonic component is comparatively very low in the Hawaiian area. It appears, however, that the variations which do exist elsewhere will lend themselves to this type of analysis, given sufficient stations to establish the regression lines.

6. Conclusions

In Hawaii, the large variations in mean monthly rainfall through short horizontal distances can be described and related in simple form by plotting the mean monthly rainfall at each station versus its own mean annual rainfall. The points representing stations on such a graph align themselves approximately in a straight line. In the equation of this line, $y = a(x - 30) + b$, the coefficients a and b represent the rainfall contribution of orography and that from general rains respectively. The lines representing the twelve mean months are significantly different, both in slope and intercept, but no significant difference has been found between islands or portions of islands.

The annual march of the slopes and intercepts define the annual march of the rainfall parameters which they represent.

There is good reason to believe that the manner of expressing the relation between stations by the plot of monthly versus annual rainfall should prove of great value in month-ahead forecasting. It is possible that pressure anomaly patterns over the Pacific as developed by Solot [6] could be correlated with the slopes and intercepts of lines representing given months. Then a forecast of the slope and intercept for an individual month would, in effect, be a forecast of the monthly rainfall total at all stations in the Territory. To interpret the forecast for any individual station, one would merely enter the curve at the mean annual rainfall of the station and read off its forecasted rainfall.

This application to forecasting is already being tested by the authors in day-to-day forecasts (24 hours in advance). Though the scatter of individual stations about their mean line is great on individual days, the method seems to hold promise even in the application to short-range forecasts.

Acknowledgment—The authors gratefully acknowledge the assistance of Dr. A. L. Tester of the University of Hawaii in the statistical analyses.

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