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RESEARCH PAPER NO. 32

Further Studies in Hawaiian Precipitation

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FURTHER STUDIES IN HAWAIIAN PRECIPITATION

INTRODUCTION

This is a report of the research conducted by the United States Weather Bureau Special Projects Section from April 1947 through November 1948, under the trust fund contract between the United States Weather Bureau, the Pineapple Research Institute of Hawaii, and the Hawaiian Sugar Planters Association.

The Hawaiian Project in Washington is mainly concerned with the problem of extended precipitation forecasts. The exploratory phase, which was fully described in a previous report [1], gave favorable indications that the problem was capable of solution. It was therefore decided to begin at once to work out details of a system of forecasting that could be readily fitted into the operational routine of the Weather Bureau Extended Forecast Section[1]. The preparation of the extended forecast consists of two distinct steps: (1) construction of mean prognostic charts, (2) interpretation of the prognostic charts in terms of weather. The first step is a general problem of the utmost complexity, to the solution of which specialized knowledge and experience of many years are being applied by the staff of the Extended Forecast Section. It was therefore decided that primary research efforts of the Special Projects Section should be concentrated on step (2).

This paper presents a resume of the research into the major problems involved in developing a practical method of interpreting the mean prognostic chart in terms of precipitation. Research like this that has specific practical aims presents certain special problems. The practical requirements must be fulfilled within the limitations of time allotted, personnel assigned, and data available. The research problem itself is so large that complete solutions are unattainable. Rather, each essential portion of the work must be brought to a stage of development from which it can be fitted into the general plan. It is often necessary to rely on meteorological judgement to take the place of time-consuming statistical tests of the soundness of certain results. Such techniques are justified because the final results are themselves amenable to rigid statistical tests. The force that binds all the individual results together into a consistent whole is a set of central meteorological ideas. Each result that fits logically into this picture or adds to its completeness may be tentatively accepted. Those results that appear contradictory or out of place must be carefully tested. If their validity is established then the whole meteorological picture must be revised. Thus, although there is a temptation to pursue a promising line of work to its ultimate conclusion, in this type of research the estimated practical benefits must be weighed carefully against the cost in man hours.

In view of these practical requirements, it was decided that the best method of accomplishing the aims of this phase of the research would be to fill in the details of the general picture of precipitation index-atmospheric flow pattern relationships that were developed in the exploratory phase. The generalized index of Hawaiian precipitation that was developed in an earlier report [1] is representative of the monthly territorial rainfall regardless of distribution, and therefore is a satisfactory representation of the Hawaiian rainfall only in months when precipitation, whether heavy, moderate, or light, is generally of the same class in all areas. Further investigation showed that this condition is representative of only a portion of the data. There are periods during which rainfall data for all parts of the territory appear well correlated and this index is adequate. But at other times the correlation of rainfall data for differing groups of stations is not high and any single index is not representative of all data.

[1] The operational phase of the project may be said to have begun in January 1948 when specialized monthly precipitation forecasts for the Hawaiian Islands were included in the forecast routine. At present this program is still on an experimental basis.

To make practical use of these general relationships therefore required that two problems be investigated; (1) What are the necessary and sufficient indices to describe Hawaiian precipitation? and (2) Can the variations in each index be recognized from mean pressure or pressure anomaly charts?

Part I of this paper presents the investigation of the first problem and considers an interesting subsidiary problem that arises in the choice of the proper units to compare precipitation at different points. It was found after completion of Part I of this work that a considerable amount of important information regarding the climatology of Hawaiian precipitation had been developed. Admittedly, this information is incomplete, being in a sense a by-product of the main line of attack. It is nevertheless presented as Part II of this paper because it forms the basis for a number of useful practical techniques, and adds to our knowledge of the fundamental atmospheric mechanisms which control Hawaiian precipitation. The second problem, that of the relationships between each index and mean charts, is discussed in Part III.

I. PRECIPITATION INDICES AND CLASSIFICATION

As stated in the Introduction, the use of a single precipitation index to describe the totality of Hawaiian rainfall, though extremely useful in preliminary studies, does not prove adequate for practical applications. Close scrutiny of the data led to the conclusion that although the rainfall correlation between various stations is occasionally very high, there are times when the relationship breaks down. This result naturally suggests the possibility of a plurality of operating causes. The problem then is to choose an irreducible minimum number of indices which will satisfactorily describe the precipitation regime.

Selection of Indices

Preliminary examination of the data showed that considerable variation exists among the rainfall regimes on the various islands. Synoptic experience indicates that the windward or northeast slopes of each island differ somewhat in rainfall regime from the leeward or southwest slopes. High correlation between rainfall amount and station elevation suggests height above sea level as possibly an important factor in the rainfall variability.

Thus it was decided to investigate the necessity of grouping stations by three physical characteristics: geographic location, aspect with respect to the northeast trade winds, and height above sea level. It was further decided to use three distinct classes for each variable. For geographical location three islands were chosen: for southeast, the island of Hawaii; for central location, the island of Oahu; and for northwest, the island of Kauai. For aspect, the classes chosen include the windward or northeast slopes, the leeward or southwest slopes of each island, and an intermediate classification designated neutral, which includes stations in central saddle areas as well as coastal stations located neither to the windward nor leeward. For height, the classes chosen are: low level stations between sea level and 100 feet, middle level stations between 500 and 750 feet, and high level stations between 1000 and 1500 feet. Since greater elevations are of little interest to agriculture, they are not considered in this study.

In order to isolate the effect of each physical property it is necessary to choose at least one sample station for each possible combination of variables. Twenty-seven stations are the minimum which may be used in this sample survey. The risk involved in choosing such a small sample to represent various regimes must be considered. Theoretically it would perhaps be better to use 54 or even 81 stations. However, two serious difficulties are encountered in an extension of the sample. In the first place it would be impossible to obtain a larger number of stations having long reliable records whose physical characteristics conform to the standards adopted. There would then be the alternative of shortening the period of study, lowering the standards, or both. The second difficulty arises from the magnitude of the task. To make the required computations for 27 stations it was necessary to process over 11,000 separate entries, each one of which had to be combined in several different ways. It would have been beyond the means of the project to double or triple this job.

The 27 stations finally used were carefully chosen with regard to representativeness, absence of location changes, and length of record. An effort was also made to spread the stations over the islands in such a manner as to avoid clustering. In classifying windward stations some account was taken of the "spillover effect", so that stations in the lee of the crests were classed as windward if their precipitation regimes were essentially similar to those of stations to the windward of the crests. Some difficulties were encountered in finding enough stations which could meet all of these specifications, especially in the case of the neutral classification. Thus in a few cases the "neutral" designation might be considered some-

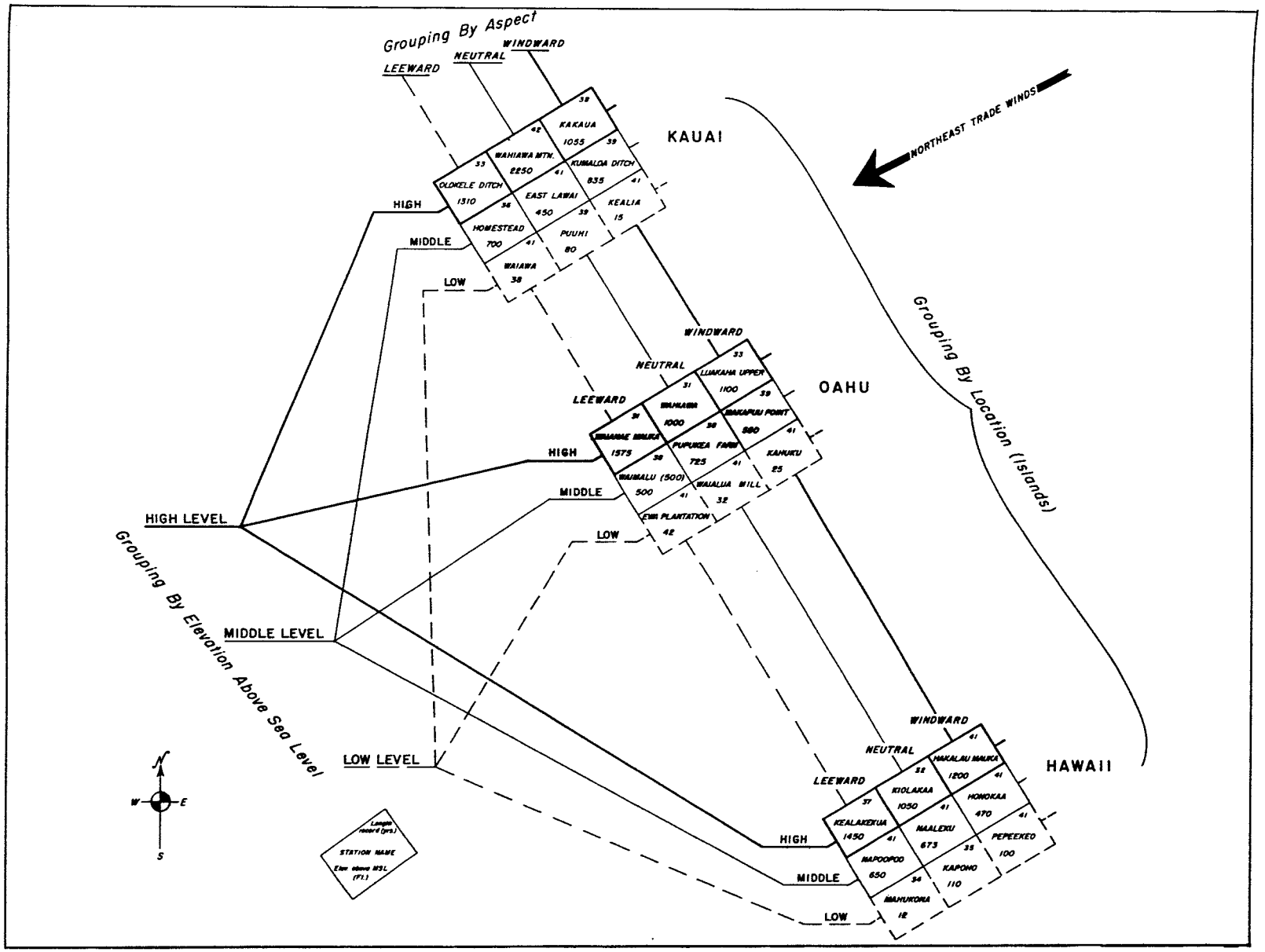

Figure 1. - Schematic grouping of stations for computation of differential rainfall calendar by elevation, aspect, and location.

what doubtful. However, this classification was later discarded for other reasons.

Figure 1 shows the samples chosen for each combination of variables[2]. When stations are grouped by a single variable, the mean rainfall of such a grouping represents variations due solely to the selected variable, since the effects of the other two are neutralized. For example, if the mean precipitation for low level stations is contrasted with that for high level stations, the variation is attributable solely to differences in elevation since both sets of data are summed over an equal number of cases of windward, neutral, and leeward aspects distributed equally among the three islands. This, of course, will be true only for a complete rainfall record; the more stations that are missing from a given mean grouping, the less reliable will be that rainfall value of the index. In this study due consideration was given the homogeneity of the record. Although the rainfall records were not adjusted for missing data, it was found that except for a few years on either end of the period 1905-1946 the records for the chosen stations are chronologically homogeneous.

Calendar of Rainfall

For the purpose of constructing a rainfall calendar, the data for the 27 stations for each month may be grouped as shown in figure 1 to yield nine different indices, each representing a mean rainfall of nine stations that constitute a class of each variable. The question of what kind of measure of rainfall to use in the computation of the indices then arises. An unweighted average of the depth of rainfall would tend to overemphasize those stations that have high normal values of rainfall. Since variation in normal precipitation among these stations is very large, it is necessary to choose some measure of rainfall that will provide a common scale. After considerable experimentation, it was found that the most satisfactory measure of rainfall for this purpose is percentile rank or accumulated percentage frequency. This quantity may be defined as the ratio of the rank of a given value in an ordered array to the total number of cases in the array, expressed as a percentage. For example, suppose that there are 40 observations of January precipitation at a particular station, and that the precipitation amount for a given January ranks eighth in ascending order of magnitude; the percentile rank of this observation would be 20. Presumably also, if the distribution of values were smooth enough this number would represent the probability of occurrence of that amount of precipitation in January at that station. In other words the probability of occurrence of a lesser amount would be about .20 as against .80 for a greater amount.

The use of percentile rank as a measure of precipitation magnitude has several important advantages:[3]

1. It provides a common scale for all stations.
2. The scale automatically adjusts itself to the density of the data, becoming finest in the region where the data are most plentiful.
3. It provides a ready means of studying directly the frequency distribution function (see Part II).
4. It expresses magnitude in the same terms as the forecast.

After the choice of percentile rank as a suitable measure of rainfall, a monthly calendar of rainfall indices was constructed, each of the nine different indices being the mean of the nine individual station percentiles comprising the particular class of the variable. No attempt was made to smooth the original frequency distribution curve for each station. To the nine indices in the calendar was added a general index which represents the mean monthly percentile of all the stations. Table 1 is a calendar of six of the ten indices. The neutral aspect index and the three elevation indices are not included in table 1 because investigations, discussed below, show them to be unnecessary.

If the rainfall indices for the two extreme classes of each parameter are correlated with one another the degree of scattering is a measure of the necessity for the designated grouping; a high degree of correlation indicates that the rainfall regime is homogeneous with respect to variations of this parameter, and therefore that particular separation is superfluous. Such a correlation analysis is graphically presented in figure 2. It can be seen that grouping by geographical location produces the greatest scatter, while the scatter for aspect, although somewhat smaller, is significant. Little difference is found between stations at high and low elevations, the degree of scatter being within the limits of observational error. When rainfall is expressed in percentiles, approximately the same value is observed at all elevations up to 1500 ft., other things being equal. It may therefore be concluded that grouping of stations by elevation is unnecessary.

[2] This method of selecting sample data is similar to the methods suggested by Azzi [3] in ecological research.

[3] Percentile rank has proven applicable in other work as well. For example in the analysis of individual rainstorms it has been found that isopercentile rainfall patterns are to a large extent independent of topography, and may be used to study storm characteristics in the same manner as isohyetal patterns are used in non-orographic regions.

Table 1.--Calendar of Hawaiian rainfall indices (mean percentiles) on which differential rainfall classification is based.

Year	January						February						March						April						May						June					
	Aspect		Geographical Locations			General	Aspect		Geographical Locations			General	Aspect		Geographical Locations			General	Aspect		Geographical Locations			General	Aspect		Geographical Locations			General	Aspect		Geographical Locations			General
	Leeward	Windward	Hawaii	Oahu	Kauai	Mean	Leeward	Windward	Hawaii	Oahu	Kauai	Mean	Leeward	Windward	Hawaii	Oahu	Kauai	Mean	Leeward	Windward	Hawaii	Oahu	Kauai	Mean	Leeward	Windward	Hawaii	Oahu	Kauai	Mean	Leeward	Windward	Hawaii	Oahu	Kauai	Mean
1905	25	27	23	27	15	21.4	7	22	23	4	18	15.1	15	30	26	18	18	21.0	17	41	23	33	27	27.6	50	54	66	39	60	51.7	34	49	50	37	47	44.8
1906	55	30	38	52	47	44.6	14	9	9	9	16	11.2	34	19	14	28	27	22.3	41	34	38	25	40	34.1	42	52	54	50	44	50.1	26	33	43	18	30	31.1
1907	90	64	53	95	98	80.5	84	81	84	78	73	78.5	70	62	59	50	92	66.7	39	32	28	31	23	27.1	68	51	34	69	73	58.2	77	67	80	74	73	76.0
1908	18	26	35	12	15	20.1	58	74	61	71	76	69.8	89	64	48	90	94	78.0	37	43	56	20	55	42.5	33	42	30	27	51	35.6	35	35	18	39	41	33.9
1909	50	47	34	53	58	48.3	60	66	67	54	47	56.0	67	86	66	77	95	79.1	42	58	48	46	64	52.6	51	51	69	41	80	46.6	58	48	32	61	59	51.0
1910	61	71	80	54	50	61.3	23	38	28	40	14	28.0	24	40	38	32	32	34.3	45	40	27	46	54	42.4	45	66	44	58	54	52.2	76	80	67	85	80	77.9
1911	73	78	70	63	89	74.0	76	83	76	86	80	81.0	62	55	70	52	60	60.2	41	43	67	30	27	40.0	37	79	65	62	53	59.5	53	72	74	49	62	61.2
1912	19	16	7	20	24	17.6	47	54	57	59	29	47.9	30	49	40	35	37	37.2	42	60	57	47	44	48.7	39	41	33	40	42	38.5	37	40	48	22	31	33.8
1913	42	47	65	32	34	43.9	36	46	40	34	58	43.9	29	37	26	40	34	29.9	65	44	48	54	56	52.8	89	62	73	88	79	80.0	89	76	69	96	94	87.2
1914	53	50	62	51	37	49.9	25	18	36	23	7	22.2	66	55	57	74	46	58.4	60	56	42	69	56	55.6	76	93	83	72	92	82.9	57	90	77	59	79	73.2
1915	9	12	14	10	5	9.5	21	46	46	29	20	32.1	18	14	8	21	14	14.1	65	85	64	86	77	75.2	32	13	36	34	8	25.6	74	73	77	66	76	73.2
1916	93	81	77	99	87	87.5	56	32	18	46	59	41.5	63	62	62	61	72	64.8	62	40	66	57	43	55.4	66	87	87	80	69	78.9	50	64	50	60	60	56.5
1917	70	68	60	86	69	71.0	62	45	48	51	63	54.3	76	81	60	97	90	81.9	72	58	57	69	76	67.3	90	59	63	79	79	73.3	56	63	54	57	62	57.6
1918	71	71	75	83	60	72.7	85	88	97	80	78	84.9	81	86	76	75	88	80.1	92	99	92	97	98	95.5	35	58	48	39	35	40.9	33	58	62	42	27	43.6
1919	30	29	27	41	12	27.0	23	21	23	17	14	18.0	30	34	35	26	28	29.8	42	41	40	41	37	39.2	38	25	33	39	31	34.5	44	38	31	61	21	37.6
1920	82	54	57	61	88	68.8	23	22	32	17	18	22.4	60	81	78	76	55	69.3	40	36	25	47	52	41.0	72	33	44	64	68	59.2	68	38	25	66	61	50.9
1921	93	97	91	94	100	94.9	50	24	47	33	32	37.6	21	37	35	21	28	28.1	36	35	31	34	49	38.2	51	27	41	40	30	37.1	35	28	18	20	56	31.5
1922	65	76	73	72	65	70.0	52	62	76	49	58	61.4	43	52	54	48	43	48.6	42	47	46	35	48	42.7	45	54	23	46	80	50.0	39	22	21	34	24	26.4
1923	89	96	93	93	91	92.7	77	68	64	84	70	72.9	81	75	84	79	81	81.3	83	83	82	86	65	76.9	39	25	48	14	44	35.9	17	31	49	14	18	26.0
1924	16	10	15	16	13	14.4	44	48	54	36	39	42.2	32	22	31	42	18	30.4	80	84	71	94	92	86.3	30	46	52	33	41	41.8	30	20	32	18	38	29.3
1925	28	48	34	41	44	39.7	21	37	12	30	51	31.6	68	60	74	66	64	67.6	54	46	34	56	61	51.1	36	42	48	35	23	35.6	33	53	56	55	30	47.0
1926	30	26	23	31	33	29.4	35	22	36	14	28	25.5	32	8	18	16	16	17.0	23	17	18	27	11	18.6	23	17	27	12	21	19.6	92	75	60	94	89	81.8
1927	64	70	54	67	64	61.9	50	39	20	511	52	41.9	78	75	60	89	86	79.1	82	78	77	86	78	80.5	70	65	36	84	90	71.3	55	47	45	64	52	54.2
1928	31	35	28	34	31	30.8	34	34	41	23	39	34.0	36	18	24	28	27	26.4	58	52	31	69	77	60.2	39	41	43	40	45	42.6	51	33	47	42	18	35.4
1929	50	46	65	36	38	45.7	66	84	80	62	52	64.2	17	38	39	17	22	25.5	50	37	65	44	29	44.4	46	46	40	53	37	43.5	39	22	35	25	20	26.4
1930	81	73	67	81	72	73.5	42	55	38	52	48	46.1	63	55	63	65	51	59.5	23	61	66	39	30	45.2	26	37	45	19	34	32.6	55	81	67	66	67	67.0
1931	18	22	14	18	30	20.4	28	36	32	22	37	30.2	41	32	36	32	37	35.2	51	38	61	37	21	39.8	56	53	61	74	47	60.8	30	22	27	21	26	24.8
1932	41	69	71	50	52	57.8	96	99	91	99	98	96.1	58	32	37	46	46	42.8	63	63	59	54	65	59.4	70	73	66	59	76	67.0	41	52	35	66	35	44.8
1933	55	72	59	57	79	65.2	80	72	52	85	81	76.0	76	70	49	86	87	74.0	47	26	63	23	33	39.8	37	51	42	41	46	43.0	61	51	45	38	77	53.7
1934	41	48	52	45	45	47.4	53	39	42	55	35	43.9	20	18	29	16	7	17.6	43	61	45	64	42	50.6	63	60	85	60	31	58.4	95	82	87	90	94	90.4
1935	66	58	56	68	52	58.9	66	83	65	86	79	76.7	55	44	53	56	55	54.6	33	27	47	15	35	32.3	36	30	45	30	14	30.6	42	47	58	42	44	48.2
1936	63	44	51	40	76	55.4	78	30	51	56	57	54.7	44	63	66	36	52	51.6	39	54	49	55	28	43.8	52	59	48	56	62	55.3	30	45	40	55	33	42.8
1937	82	83	91	78	70	79.5	84	82	86	89	77	84.5	62	78	71	60	78	69.6	49	59	45	68	59	57.3	74	87	79	83	74	78.6	39	37	63	43	19	38.8
1938	54	66	67	54	70	63.9	86	90	79	90	97	88.2	68	75	64	68	72	68.1	60	62	78	70	35	61.4	68	71	84	81	46	70.8	75	61	53	64	99	68.4
1939	39	54	62	43	32	45.1	63	73	70	61	87	73.3	81	78	86	79	80	81.8	84	85	82	78	87	82.8	78	58	31	65	87	62.1	56	47	62	53	58	57.2
1940	62	36	33	58	55	48.7	26	42	39	38	24	33.3	49	43	56	49	34	46.2	46	40	31	50	40	40.0	68	72	40	89	86	70.9	47	27	40	26	37	34.7
1941	27	38	34	24	24	28.3	24	26	30	15	20	21.9	29	35	36	25	22	28.0	24	24	37	7	15	20.2	41	67	67	52	42	53.6	47	65	69	64	36	56.2
1942	25	28	13	14	47	24.8	55	58	45	57	53	51.6	62	77	84	61	56	67.0	56	80	50	67	81	66.0	33	58	51	42	46	46.4	59	70	58	72	81	70.2
1943	84	66	66	89	84	79.2	47	56	49	54	44	49.2	56	47	67	52	37	52.6	22	31	42	22	16	26.9	85	61	62	91	76	76.4	49	65	78	36	74	62.1
1944	18	15	22	11	16	16.6	77	83	80	79	93	83.6	96	50	49	92	89	76.3	31	31	42	21	13	25.9	56	54	70	40	56	55.1	78	60	66	75	66	69.2
1945	12	11	20	11	4	12.1	38	29	47	31	31	36.7	36	54	68	22	42	44.9	96	68	64	95	99	85.6	43	13	31	22	29	27.2	41	48	76	27	21	42.3
1946	76	72	84	71	66	73.9	72	67	68	64	93	74.7	40	44	43	34	47	41.3	53	55	47	30	87	55.6	21	18	25	12	9	16.0	51	43	28	55	55	45.4

Table 1.--Continued

Year	July Aspect Leeward	July Aspect Windward	July Geographical Locations Hawaii	July Geographical Locations Oahu	July Geographical Locations Kauai	July General Mean	August Aspect Leeward	August Aspect Windward	August Geographical Locations Hawaii	August Geographical Locations Oahu	August Geographical Locations Kauai	August General Mean	September Aspect Leeward	September Aspect Windward	September Geographical Locations Hawaii	September Geographical Locations Oahu	September Geographical Locations Kauai	September General Mean
1905	45	59	54	65	35	51.3	80	72	72	74	75	73.4	66	77	80	70	53	68.3
1906	22	44	48	28	17	32.7	56	75	76	55	81	70.2	33	45	29	49	44	39.6
1907	65	68	66	61	83	70.6	75	90	88	80	88	85.7	64	76	92	73	33	65.6
1908	19	26	32	7	15	17.8	46	51	39	38	49	40.8	50	67	46	72	54	57.8
1909	54	72	50	71	65	62.5	24	27	24	15	40	25.5	33	36	40	26	41	35.3
1910	50	47	52	55	40	48.6	46	67	60	80	37	59.0	80	50	41	78	73	65.1
1911	51	55	40	41	81	55.2	31	58	50	48	17	37.6	75	91	70	78	92	80.8
1912	41	37	31	44	34	36.3	42	42	24	53	34	36.8	20	26	29	13	19	20.3
1913	55	46	42	24	31	32.7	62	45	48	71	39	52.7	37	28	23	45	41	36.3
1914	37	85	75	60	46	60.6	62	64	96	46	53	65.7	81	96	77	94	100	90.3
1915	57	62	65	63	48	58.5	38	33	24	25	55	35.4	79	52	48	48	80	59.6
1916	55	66	55	65	56	58.4	46	59	54	59	37	49.5	43	54	46	36	52	45.1
1917	66	27	31	40	62	44.8	55	24	22	50	49	40.1	65	31	24	68	50	46.7
1918	51	70	80	57	62	66.3	75	77	63	89	66	72.8	49	19	32	48	30	36.8
1919	59	43	34	45	61	46.7	31	24	36	33	16	28.5	51	37	36	57	47	46.5
1920	65	45	40	72	46	51.8	50	53	26	54	78	52.7	55	56	56	37	79	57.2
1921	50	44	43	58	42	47.7	38	39	43	37	37	39.3	36	34	28	37	49	37.8
1922	32	26	46	29	10	28.6	43	35	33	34	31	32.9	71	86	60	85	84	76.4
1923	41	30	39	16	44	33.5	31	34	64	20	20	33.0	37	42	55	37	32	40.1
1924	51	48	49	65	65	60.0	24	28	34	33	19	28.8	24	22	43	25	8	25.4
1925	43	35	36	56	49	47.7	36	37	62	27	22	35.9	30	60	51	48	39	46.9
1926	50	25	40	45	30	38.3	58	56	77	63	30	55.7	40	50	31	38	52	40.9
1927	61	65	46	68	63	59.6	38	58	50	47	56	50.8	71	61	77	74	46	65.2
1928	60	73	65	65	81	70.6	42	43	46	30	50	41.6	26	56	55	22	51	42.0
1929	53	66	51	39	91	60.8	76	59	64	72	62	66.2	41	19	41	36	22	33.3
1930	19	61	48	47	42	45.6	48	76	63	42	76	60.3	81	89	76	86	92	84.6
1931	47	52	74	46	23	47.7	84	73	56	88	92	79.1	56	87	66	80	69	71.9
1932	52	55	45	45	60	49.8	55	48	28	60	65	50.6	38	36	45	46	33	41.0
1933	47	38	18	49	60	41.4	34	20	24	27	25	25.6	39	37	37	29	40	35.3
1934	65	49	63	54	47	54.4	50	23	49	45	8	35.3	89	80	80	86	75	80.4
1935	65	61	65	63	43	56.8	34	32	32	34	57	39.8	73	69	62	72	90	74.6
1936	68	72	68	67	85	73.4	73	88	76	87	86	83.3	71	66	70	70	59	66.6
1937	83	89	83	90	83	85.6	74	62	71	62	83	71.9	38	55	45	49	52	48.5
1938	61	46	44	70	64	59.5	83	68	55	95	80	76.0	25	27	44	12	21	26.4
1939	55	52	58	54	52	54.7	31	30	19	39	33	30.0	48	33	49	72	9	42.0
1940	57	67	57	37	79	58.8	78	91	89	69	86	81.5	39	54	57	34	50	47.6
1941	24	44	51	30	18	33.0	58	76	66	60	66	64.2	67	66	89	48	68	69.2
1942	55	43	30	69	45	48.3	51	49	63	48	36	48.8	53	41	51	44	59	51.0
1943	51	47	70	26	34	43.4	58	51	60	34	89	59.7	49	33	39	23	55	38.3
1944	37	57	61	30	61	50.1	35	34	42	26	36	34.6	24	28	51	17	9	26.2
1945	74	26	45	75	22	48.1	62	60	50	71	76	65.1	47	16	34	48	24	36.3

Year	October Aspect Leeward	October Aspect Windward	October Geographical Locations Hawaii	October Geographical Locations Oahu	October Geographical Locations Kauai	October General Mean	November Aspect Leeward	November Aspect Windward	November Geographical Locations Hawaii	November Geographical Locations Oahu	November Geographical Locations Kauai	November General Mean	December Aspect Leeward	December Aspect Windward	December Geographical Locations Hawaii	December Geographical Locations Oahu	December Geographical Locations Kauai	December General Mean
1905	35	50	47	44	47	46.1	66	77	69	64	94	74.9	29	41	45	29	17	31.9
1906	45	37	27	46	34	35.5	83	63	74	82	60	73.0	79	77	76	83	74	77.9
1907	28	56	69	37	19	41.5	46	40	41	37	50	42.4	35	37	25	39	42	35.3
1908	16	45	37	17	37	29.8	17	26	29	19	7	18.6	36	39	56	25	15	31.3
1909	33	42	33	39	47	39.8	9	12	8	15	9	10.7	87	82	82	82	89	84.6
1910	35	58	42	26	53	40.3	58	68	40	66	92	67.1	46	62	55	54	53	54.1
1911	42	37	48	38	17	33.9	34	44	57	27	22	34.5	44	36	54	40	33	42.0
1912	49	55	62	56	44	54.1	36	42	41	43	30	37.9	56	49	48	51	58	52.5
1913	73	40	40	63	76	60.6	78	88	84	75	91	83.4	10	42	37	22	8	22.5
1914	18	28	31	26	18	25.0	58	65	83	46	47	59.5	71	65	87	55	61	67.9
1915	57	66	76	57	68	67.2	90	90	92	92	87	90.1	86	79	75	91	93	86.2
1916	74	55	64	62	67	64.4	56	68	46	62	80	62.5	75	90	86	81	81	82.8
1917	74	32	42	50	63	51.6	45	61	43	66	36	47.8	62	34	53	68	38	52.3
1918	41	42	36	52	34	40.5	90	73	76	89	83	82.7	48	70	43	61	59	54.5
1919	43	46	40	51	65	52.2	28	28	25	25	42	30.7	54	46	41	35	78	51.3
1920	55	68	64	30	76	57.0	47	52	26	62	62	50.0	79	66	57	86	81	74.5
1921	54	59	44	72	44	52.6	35	49	59	30	15	35.0	82	79	65	72	88	75.0
1922	51	56	41	58	70	56.4	50	70	57	49	72	59.2	14	7	25	6	4	11.7
1923	45	57	45	43	51	46.7	18	20	30	17	19	21.4	83	85	86	84	82	84.0
1924	54	78	66	66	72	68.0	47	28	57	27	40	40.5	71	33	45	56	50	50.3
1925	54	39	47	52	42	47.0	46	43	45	63	33	47.0	46	13	30	35	44	36.7
1926	46	36	50	60	16	41.6	25	22	34	21	10	21.2	47	33	52	25	58	43.4
1927	40	33	53	25	24	33.2	64	71	54	80	60	64.9	95	95	95	100	94	96.3
1928	38	42	48	41	42	43.2	84	60	44	75	94	72.3	42	43	57	36	20	37.6
1929	57	40	31	55	54	46.8	90	73	83	89	83	84.8	64	76	81	91	34	68.3
1930	65	62	60	77	69	68.3	77	88	75	85	84	81.1	14	25	22	15	20	18.9
1931	51	73	60	66	64	63.7	43	60	51	48	47	48.5	28	41	24	33	34	30.6
1932	35	21	12	30	41	27.6	71	57	46	72	87	68.0	40	56	62	38	48	49.7
1933	9	7	15	4	8	9.0	31	21	40	22	15	25.5	54	42	21	63	62	48.6
1934	60	69	68	80	61	62.9	52	58	58	56	50	55.2	38	33	50	35	39	41.5
1935	72	53	74	81	39	64.3	62	54	76	58	51	61.7	25	31	28	18	41	28.9
1936	85	95	88	95	94	92.2	53	45	42	48	45	45.0	60	70	68	65	63	65.4
1937	62	64	64	50	75	62.9	48	49	39	45	51	45.0	48	62	53	76	58	62.3
1938	58	42	64	45	32	47.9	38	48	46	41	64	50.2	25	49	46	42	26	37.8
1939	81	79	50	100	94	80.5	64	64	69	64	56	62.8	25	20	24	22	27	24.3
1940	65	75	71	45	92	70.0	73	57	74	92	34	65.8	20	29	23	24	20	22.2
1941	84	90	92	93	80	88.5	17	34	36	10	30	25.6	22	34	26	25	24	25.2
1942	68	53	55	90	23	57.2	52	39	27	57	77	52.7	88	69	58	86	99	79.9
1943	37	16	22	28	39	29.3	30	13	20	13	30	20.7	44	46	39	41	54	44.6
1944	36	44	59	36	7	35.2	32	35	36	38	27	34.0	57	47	72	47	49	56.4
1945	48	55	51	24	73	48.5	43	37	52	43	47	47.1	61	71	63	66	73	67.0

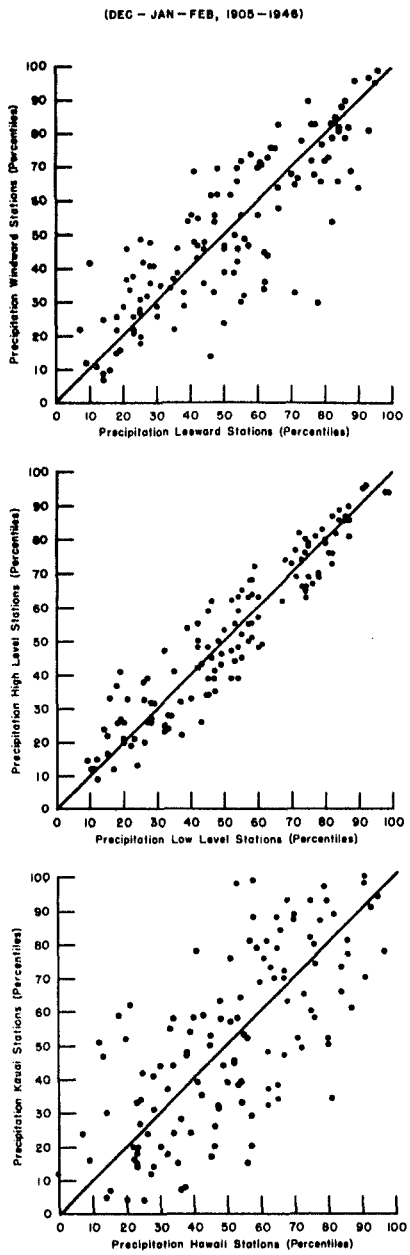

Figure 2. - Scatter diagrams showing rainfall correlation between stations with contrasting characteristics.

Classification of Rainfall

Examination of the percentile values of rainfall shown in the calendar of table 1 indicates that rainfall regimes on some occasions are remarkably similar for all groupings, while at other times a dissimilarity of regimes is noteworthy. When regimes are similar throughout, rainfall may be classified as general, and a single index will be adequate. In January 1921 for example, the rainfall was heavy for all station groups. This then represents a month of general heavy rain. An example of general light rain is the month of January 1924 where the entire range of values lies between 10 and 16. Again a single index is adequate for a description of the rainfall.

When regimes for the various groups of stations are dissimilar, the rainfall may be classified as stratified and several indices are then necessary. In February 1936, the rainfall data are stratified in such a manner that heavy rainfall (78) is observed as the mean value for leeward stations while light rainfall (30) is observed as the mean for windward stations. Here a definite stratification by aspect is indicated in the rainfall regime. Examples of stratification by location may be observed in May 1934 and May 1939. In May 1934 there was heavy rain (85) on Kauai and light rain (31) on Hawaii. In 1939 the May rainfall values indicate light rain (31) on Kauai and heavy (87) on Hawaii.

Analysis of the calendar therefore leads to a differential rainfall classification based on the stratification regime. This is shown below:

Differential rainfall classification

1. General precipitation
2. Stratified precipitation
   a. By location (islands)
   b. By aspect

II. PRECIPITATION PATTERNS

The statistics of the sample survey discussed in the previous section throw considerable light on the climatology of Hawaiian precipitation and the atmospheric mechanisms which operate to produce precipitation. These findings based on summaries of the entire record of 42 years (1905-1946), are discussed in this section.

Stratification by Aspect and Location

The absolute deviation of the mean rainfall foı any group of stations from the mean for all stations is a measure of the group tendency toward stratification . Table 2 shows the tendency for stratification by aspect and by location.

Table 2. Mean absolute deviations from mean precipitation for all stations (expressed in percentiles).

Aspect		Location	
Leeward Stations	6.05	Hawaii	9.74
Neutral Stations	4.76	Oahu	7.56
Windward Stations	6.51	Kauai	9.15
Mean	5.77	Mean	8.82

It may be seen that stratification is greater by location than by aspect. Whereas windward stations show a slightly greater stratification tendency than leeward, neutral aspect stations show considerably less than either. In fact there is reason to suspect that the neutral classification is quite artificial. It consists of at least two different types of stations namely, those stations located on the northwest and southeast coasts of islands, and stations located in the saddle between two ridges. It is evident that particularly the saddle stations will tend to receive their heaviest precipitation as spillover from either strong northeast or southwest flow patterns.

To interpret the tabular results in the category of location it is necessary to discuss the meaning of stratification by location. This type of stratification might result either from the inherent topographic differences of the islands, or from a tendency toward systematic latitudinal[4] gradients of precipitation patterns in individual months, or both. In the former case a more or less random interisland distribution of precipitation patterns for the month would be expected. This would result in practically equal values of mean absolute percentile deviations. However, if the normal patterns of precipitation of the three islands are examined, it is obvious that Hawaii and Oahu are more nearly like each other than like Kauai. If, therefore, any significant difference in stratification index arises, the value for Kauai would be expected to be highest. On the other hand, if stratification is the result of systematic latitudinal precipitation gradients the central island should show a lesser deviation from the mean than the extremes of the island chain. The results indicate that the three indices are not equal, that Kauai is not the highest, and that Oahu is markedly less than the others. This tends to lend weight to the second hypothesis. This important point will be dealt with more fully in later discussion.

[4] Longitudinal gradients are probably of some importance but it is believed that the latitudinal gradients are of much greater importance.

Annual Variation of Stratification

The annual variation in the stratification of rainfall should shed some light on the problem of the interpretation of stratification. It was found, however, that because of the drastic reduction of precipitation range in summer it is not feasible to use absolute percentile deviation as an index of annual stratification. Therefore, somewhat arbitrary standards were adopted for the tabulation of the monthly frequencies of occurrence of general and stratified precipitation. Precipitation for a given month was defined as general whenever the greatest difference between any two groups of stations was less than 20 percentiles. Stratification by aspect or location was defined by a percentile difference greater than 30 between any two station groups. Two considerations governed the choice of the above criteria, namely that a sufficient number of cases should be found in each class, and that the sensitivity of the separation should in general conform to the tertile system used in forecasting. It will be noted that the above definitions are not contiguous, and borderline cases were omitted from the tabulation. Results of this tabulation are shown by graphically smoothed frequencies in figure 3. Little significance can be ascribed to the relative magnitudes of the curves since the criteria were arbitrarily chosen. It may be seen that general rains have a maximum frequency in winter and a minimum in summer. This coincides fairly well with the variation of intensity of perturbations in the westerlies, a result not entirely unexpected. By definition, of course, the stratified precipitation should show the opposite tendency. It is of interest to note the more complex character of the curve for stratification by location.

To investigate stratification by location more fully a more detailed and accurate analysis by islands was attempted. Monthly precipitation for a given island was defined as stratified if it deviated from the mean precipitation by more than 15 percentile. Frequencies of occurrences of stratified precipitation, thus defined, are shown in figure 4. Again the minima occur in winter, coinciding with maximum general precipitation. However, a definite latitudinal shift of minima is observed from late January on Hawaii to late February on Kauai. The most noteworthy features of these curves are the seasonal differences in maxima between Hawaii and Kauai. These are coincident with the retreat of the westerlies northward and the corresponding advance of the easterlies. In the early spring the northern portion of the islands are still under the influence of the westerlies, so that the Hawaii easterly regime tends to differ from the rest of the islands. As the easterlies advance farther and farther northward the region of maximum stratifi-

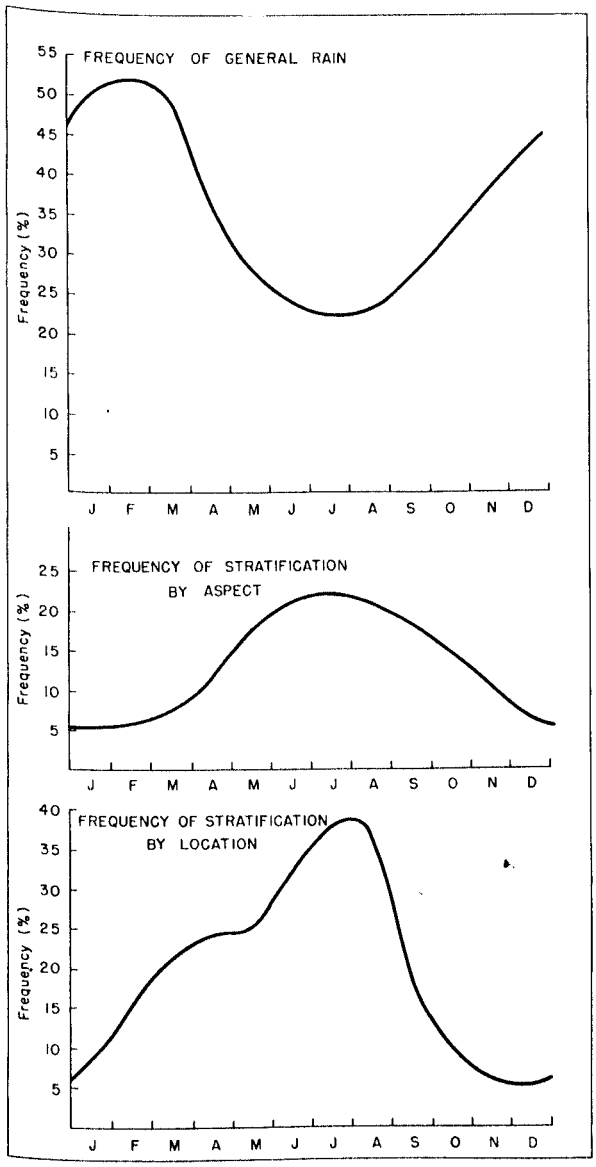

Figure 3. - Annual frequency curves of general and stratified rain.

cation tends to shift toward Kauai. The intermediate character of the Oahu curve is clearly evidenced by its resemblance to Hawaii in the early spring and then to Kauai in the summer months. This may be interpreted to mean that even though the latitudinal extent of the Islands is small, they lie in a very critical boundary zone between the circulations of high and low latitudes.

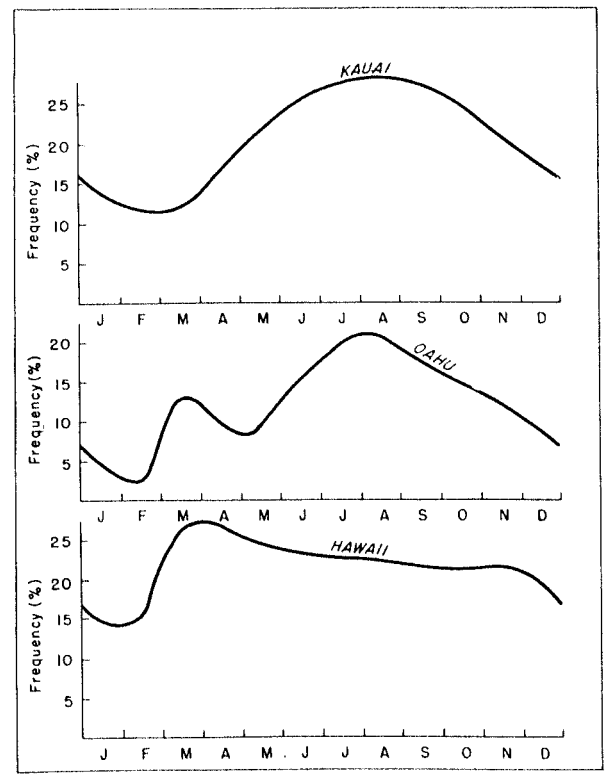

Figure 4. - Annual frequency curves of rain stratification by islands.

Annual Variation of Precipitation Intensity

Further knowledge is gained by consideration of figure 5 which shows the annual variation of monthly precipitation intensities grouped according to the basic classification scheme. In this study the median instead of the mean is used as a measure of the normal and all values are adjusted to a 30 day month. Classification by islands was omitted from the chart because curves for all islands exhibit essentially the same pattern as the mean curve.

The curve for windward stations is characterized by three maximum points: in March, August, and December; and three minima: in February, June, and September. Similar types of curves were found at stations on Oahu by other invesitgators, particularly Landsberg [4] and Riehl [5]. The summer maximum is probably associated with the seasonal increase in trade wind circulation. Riehl ascribes the two summer minima to the alternate northward

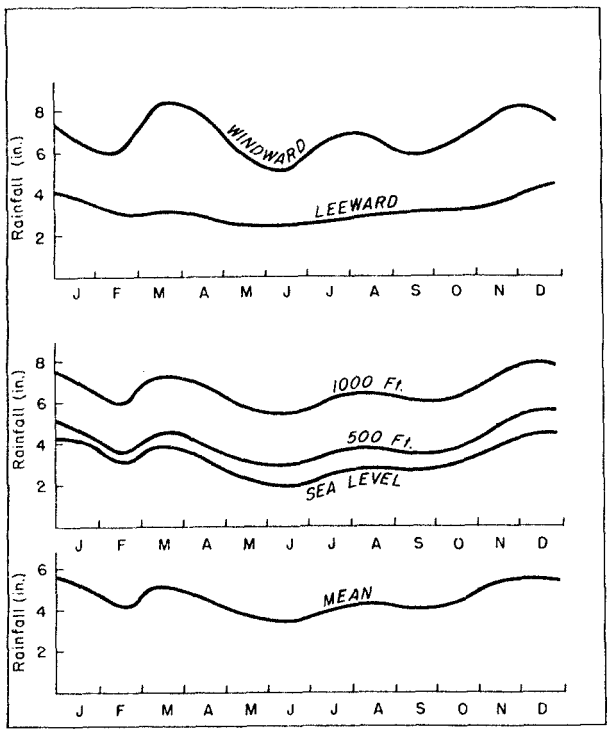

Figure 5. - Annual curves of median precipitation.

and southward seasonal shift of the subtropical ridge-line. He further points out that "interaction between disturbances of high and low latitude is the most potent rain-producing factor throughout the trade wind belt.....It may now be argued, however, that in those months when extratropical control over the northern hemisphere attains its maximum, formation of low latitude perturbations is most restricted. The frequency of superposition of high and low latitude disturbances therefore presumably is less in those months than in December or March, or at least the low latitude troughs are less potent." This affords a reasonable explanation of the double maxima in winter.

The above hypothesis appears to fit the known facts well. From recent studies it has been found that the ideal synoptic pattern for the production of general heavy rain consists of the juxtaposition of a trough in the westerlies and a low latitude easterly trough. Moreover, it is now known that the record breaking rainfall amounts, on the windward sides of the islands, at least, come from this type of storm.

The data for leeward stations present a picture rather different from the windward curve. Here a simple curve with a maximum in winter and a minimum in summer is found. This leads to the conclusion that in general the normal leeward rainfall varies inversely with the strength of the easterlies, and directly with the intensity of the westerlies. Presumably the sea breeze, itself an important rain producing mechanism over the leeward portions of the islands, correlates inversely with the trade wind [6]. In winter the maximum is intensified by the passage of westerly troughs to the north of the islands producing the "Kona" type storm.

A rough comparison between precipitation values at various elevations shows that the relationship between elevation and precipitation is non-linear within the limits shown.

Frequency Distribution of Precipitation

After exploration of the nature of the annual variation of normal (median) precipitation, the next problem which naturally presents itself is the distribution of precipitation about the median and specifically the effect of season, elevation, aspect, and geographical location on the frequency distribution curves of precipitation. Although most of their studies have been confined to the island of Oahu, a number of investigators have studied the distribution of rainfall on the Hawaiian Islands. Notable among these are Voorhees [7] who studied the average annual rainfall of Oahu; Nakamura [8] who constructed ogive curves of accumulated frequencies of annual precipitation amounts for selected stations on Oahu, investigated the geographic distribution of the coefficients of variability of these curves, and obtained a set of curves showing the probability of less than a given amount of rainfall occurring annually at selected stations; Wentworth [9] who investigated ratios of interstation and annual rainfall values to the means, and their variation; Landsberg [4] who collected a wealth of data on rainfall at selected stations on Oahu and demonstrated the superiority of the median over the mean as an expression of normal rainfall on Oahu, where the distribution is skew; and Jones [10] who emphasized the need for more detailed study of the vagaries of rainfall and called for a "de-averaging of Hawaiian rainfall data" as essential to meteorological understanding. All investigators noted the extreme skewness of Hawaiian rainfall distribution curves.

In this investigation, a characteristic frequency distribution curve was obtained for each of the nine different station groupings. To show the effect of season, two additional curves were obtained by combining the data by the nine station groupings for the months of January and July. Finally, the set of characteristic frequency distribution curves was completed by using all data to construct a mean curve. To provide a common basis of comparison

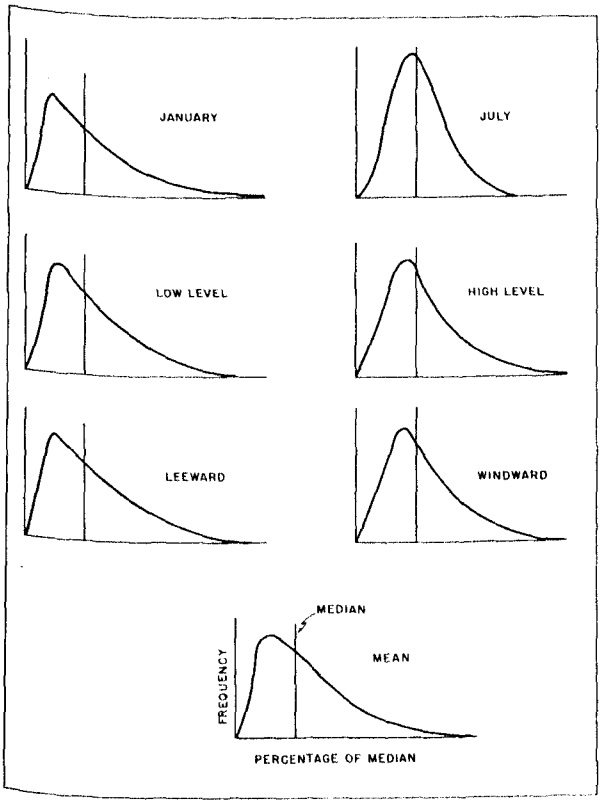

Figure 6. - Frequency distribution curves of Hawaiian rainfall showing effect of season, elevation, and aspect.

among these 12 curves, the precipitation was expressed as a percentage of the median. It was found that the 12 curves can be reduced to 7 since the curves for neutral and middle level stations are indistinguishable from leeward and low level stations respectively, and no important differences were found among the curves for the three islands. These 7 characteristic distribution curves are presented in figure 6. The most striking differences are between January and July, and the variation in characteristic distribution curves occurs, in order of importance, with (1) season, (2) elevation, and (3) aspect.

To apply physical reasoning to the detailed variations in the distribution curves would require a degree of knowledge far beyond the frontiers of contemporary meteorology. Nevertheless, certain broad phases of the problem seem to be related to physical principles. As previously mentioned, all investigators have commented on the skewness of the distribution of Hawaiian precipitation. It is apparent however, that the skewness varies greatly between winter and summer. It seems reasonable to postulate that any rain-producing mechanism which has great regularity will tend to introduce a certain amount of symmetry in the distribution curve. Thus the trade winds which are relatively constant will produce precipitation values more or less randomly distributed about some central value. On the other hand, any rain-producing mechanism which is itself subject to wide variations in frequency and intensity will introduce

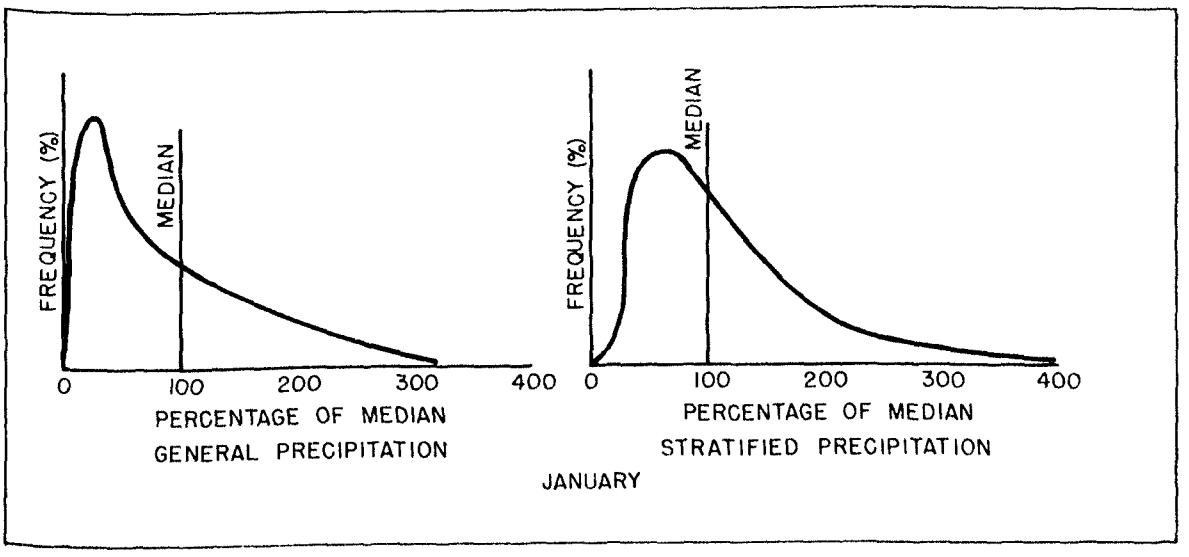

Figure 7. - Frequency distribution curves showing comparison of general precipitation and stratified precipitation in January.

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skewness in the rainfall distribution curve. The general storms in winter could, accordingly, be largely responsible for asymmetry of the curves in that season.

The above hypothesis was tested by breaking down the January data into two separate distributions, one for general precipitation, and one for stratified precipitation. As can be seen in figure 7, the curve for general precipitation is by far the more skewed of the two. However, even the stratified precipitation curve in January is considerably more skewed than the July curve. This could be explained in two ways: (1) the trade winds are more regular in summer; (2) there is another type of precipitation not hitherto considered which is more prevalent in summer than in winter. This could be the local diurnal convective showers [6], which of themselves produce small amounts of rain, but which are very frequent in summer.

From a combination of the data illustrated in figure 6 a set of characteristic curves for each type of station for each month was computed. The curves for January and July are shown in figure 8. From these basic data and from the median precipitation obtained from Halstead and Leopold [11] it is now possible to construct a set of rainfall probability tables for any station below 2000 ft. in the Hawaiian Islands. These tables, which are too long for publication here, have many practical uses, among which are long range operational planning, standardization of class limits for forecast verification, extension of data for stations with short record, and further refinement of forecasting techniques.

III. PRESSURE AND PRESSURE-ANOMALY PATTERNS

It has been shown that the monthly precipitation occurs in a variety of distinct patterns which can be quantitatively classified. The problem arises to determine whether circulation patterns can be found that are uniquely associated with precipitation patterns. Extensive investigation confirmed the previous view [1] that the mean pressure anomaly chart is a satisfactory tool for this purpose. It would be most desirable to extend the analysis to the upper air. However, since sufficient upper-air data are practically non-existent we are forced to resort to sea level data. Fortunately it is known that the large scale systems in the Eastern Pacific are composed predominately of warm highs or cold lows and presumably the mean sea level patterns reflect to a considerable extent the upper air patterns.

Composite Pressure Patterns

The basic method of attack, the construction of composite charts, was fully discussed in a previous report [1]. Essentially, it consists of choosing a number of outstanding examples of each class of precipitation pattern, and computing the mean pressure-anomaly chart for the sample. In this study the procedure was modified in one respect. Instead of averaging the individual values of pressure anomaly at each grid point, the anomaly values at standard points on each map were ranked in order of magnitude, and the individual values of rank at each point were averaged. This equalizes the effect of each individual map on the composite and preserves the mean pattern independently of the gradient.

The choice of sample months was of course made solely on the basis of the rainfall classification. This includes a set of 14 classes: general heavy rain, general light rain, and heavy and light rain for three stratifications each by islands and by aspects. The data were further divided into winter and summer cases. Only the winter cases are shown here, since no important differences could be found between winter and summer patterns. In choosing the cases to be included in the general rain classifications it was decided to use the best examples of general heavy and light rain. Since these included the most extreme rainfall cases they were quite easy to select. In the stratified classes those months were chosen in which rainfall for the class under consideration was at least 70 percentile for heavy rain or at most 30 percentile for light rain and respectively greater or less than the mean for all stations by at least 20 percentile. It was necessary in a few instances to relax the requirements slightly in order to obtain sufficient cases for each class. The sample months, except for the neutral aspect stratification, are enumerated in table 3.

Composite charts for light and heavy rain for general, stratified leeward, and stratified Hawaii are shown in figures 9 to 14. The most striking feature of these charts is the degree of contrast between the light and heavy rain patterns in each case. It was found in fact that in all of the patterns, with the exception of neutral aspect, the light-rain chart is opposite in flow to the corresponding heavy-rain chart. Since the component months were chosen independently, on the basis of rainfall class without reference to their flow patterns, it is inconceivable that these contrasts are coincidental. Thus the conclusion is forced that these patterns are significantly related to their rainfall

Table 3.--Months used in construction of composite charts for stratified rainfall

Stratification	Month	Heavy Rain	Light Rain
		Year (19--)	Year (19--)
General	Dec.	09, 15, 16, 23, 27	22, 30
	Jan.	16, 21, 23	05, 08, 12, 15, 24, 31
	Feb.	11, 18, 32, 37, 38	05, 06, 14, 19, 20
Windward	Dec.	16, 18	17, 25
	Jan.	10, 27	06
	Feb.		21, 36
Leeward	Dec.	24	13, 38
	Jan.	07, 20	25
	Feb.	36	15, 25
Kauai	Dec.	19, 21	05, 08, 28, 29
	Jan.	07, 11, 33, 36	19, 39
	Feb.	39	10, 12
Oahu	Dec.	20, 29, 37	19, 26, 35
	Jan.	17	
	Feb.	23	26
Hawaii	Dec.	14	07, 33
	Jan.	10, 32, 37	12
	Feb.	22, 29	16, 25, 27

classes. One example of an individual monthly pattern is shown with each composite (figs. 9-14). The general resemblance between these patterns and their corresponding composites without regard to the gradients is well marked. This shows further that the composite patterns are real in the sense that they are not merely artificial products of the technique employed.

It was previously pointed out that there are a priori reasons for questioning the validity of the neutral-aspect classification. This is well borne out by the fact that the corresponding composites are not well contrasted. For these reasons the neutral aspect was eliminated as a significant rainfall class.

Ideal Patterns

Since for all practical purposes the remaining light- and heavy-rain composites may be considered as opposites, it was decided to combine them. This was done by reversing the ranks of the pressure-anomaly value of the light-rain cases and averaging them together with the ranks of the heavy-rain months. This essentially doubles the number of cases in each composite. Thus a set of six "ideal" heavy-rain charts were obtained which may be completely reversed by relabeling the high and low anomaly centers to obtain "ideal" light-rain charts. These are shown in figures 15 to 20.

The general-rain pattern (fig. 15) is quite similar to the basic pattern discussed in the previous report [1]. It will be noted that the leeward (fig. 16) and windward (fig. 17) patterns are fundamentally opposite. No difficulty is encountered in their interpretation. An intense northeasterly flow produces upslope flow on the windward slopes of the islands and downslope flow on the leeward sides. On the other hand, strong southwesterly flow produces the opposite effect. The Oahu pattern (fig. 19) being intermediate resembles the general

Table 4.--Months used in construction of composite charts for rainfall stratified windward and leeward on each island.

Stratification	Month	Heavy Rain	Light Rain
		Year (19--)	Year (19--)
Kauai Windward	Dec.	19, 21	08, 11, 17, 25, 28
	Jan.	11, 20, 33	13
	Feb.	08, 39	12, 14, 34, 36
Kauai Leeward	Dec.	19, 26	05, 08, 13, 29
	Jan.	07, 20, 36	19
	Feb.	36	10, 15
Oahu Windward	Dec.	38	19, 25
	Jan.	16, 17	29
	Feb.	33	26
Oahu Leeward	Dec.	17, 20, 29	32
	Jan.	07, 30, 35	13, 25, 32
	Feb.	12, 16, 23	13, 25
Hawaii Windward	Dec.	08, 10, 18, 36	17, 24, 25, 33
	Jan.	13, 32, 39	06, 07, 20, 36
	Feb.	12, 15, 22, 29	16, 17, 25, 36
Hawaii Leeward	Dec.	14, 17, 24, 29	10, 18, 33, 38
	Jan.	10, 14, 20, 30	09, 25, 34
	Feb.	17, 24, 36	10, 12, 13, 25

pattern (fig. 15) except for the trough near the islands. There remains the difference between Hawaii (fig. 18) and Kauai (fig. 20) which is fundamentally a difference in kind rather than in sign. This will be discussed in a latter section where the patterns will be interpreted more fully.

It seemed desirable further to subdivide the patterns into windward and leeward stratifications on each island. This could be done in two ways: (1) by adding the aspect and island patterns together; for example, to get the ideal pattern for Hawaii windward stations add the ideal Hawaii pattern to the ideal windward pattern; (2) by separating the precipitation data for each island into windward and leeward stations, computing a new rainfall calendar, going through the same process of selection of representative months as described above, and constructing new composite charts. The second method is of course by far the more laborious, but the results are independent of the first set of composites, and may thus serve as an excellent check on the reliability of the patterns. The second method was used on all rainfall types. The results were compared in a few test cases with those derived from the first method and the two sets of patterns proved to be very nearly identical. The sample months selected for each composite are shown in table 4 and the resulting ideal pressure anomaly patterns are illustrated in figures 21 to 26.

Interpretation of Patterns

The idea of relating anomalies of weather to pressure anomalies is a very old one in meteorology. G. Walker [12] and others, using the records of Clayton [13], attempted to correlate the mean pressure anomaly at selected points with the ensuing weather at other points. From the foregoing it is evident that, with regard to Hawaiian precipitation, at least, the pattern of the anomaly chart is of more importance than the values of the pressure anomalies, or even the anomaly gradient. It is only in recent years that the extent and reliability of the observational network have so

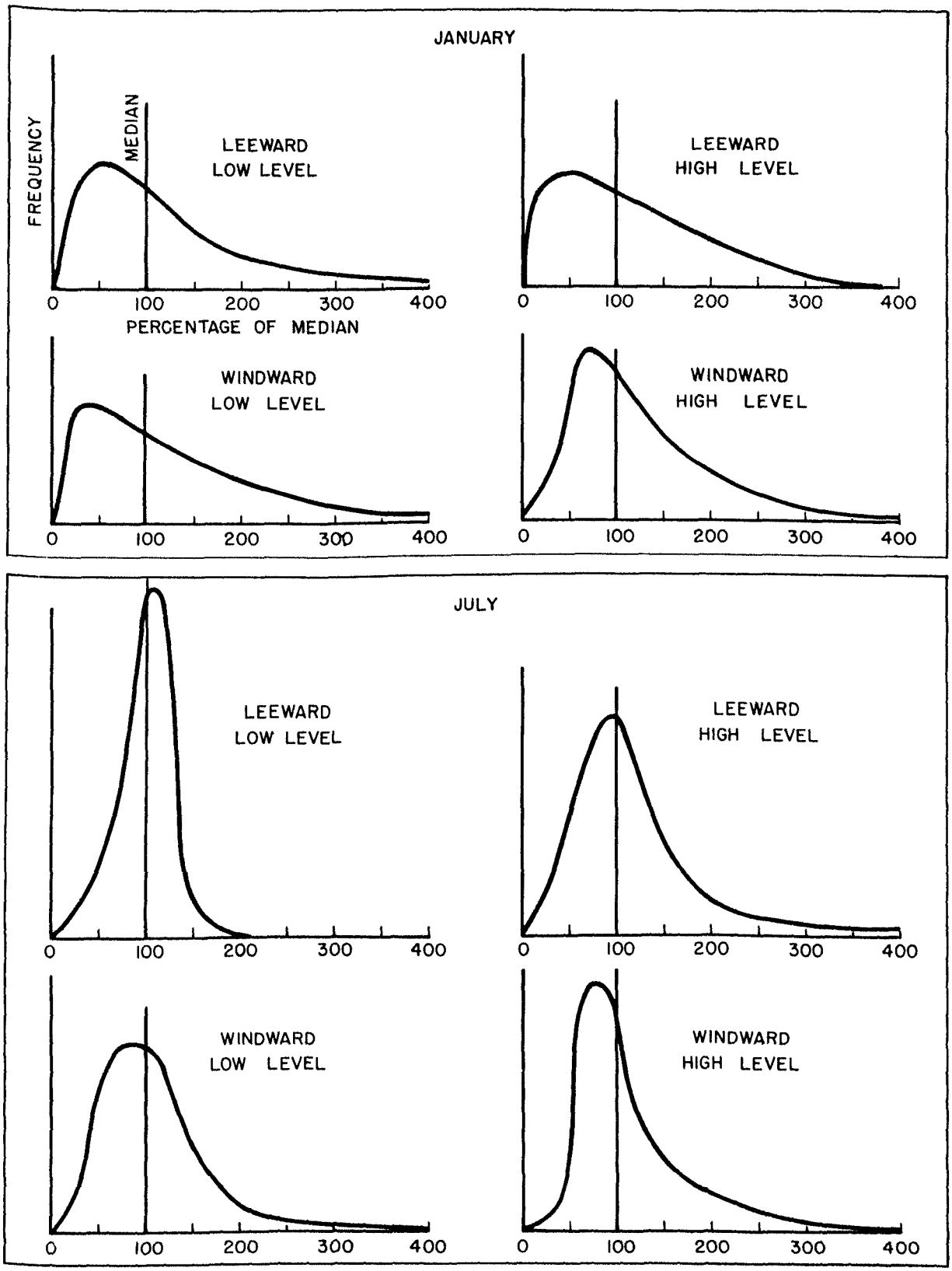


Figure 8. - Frequency distribution curves showing comparison of Hawaiian rainfall stratification for January and July.

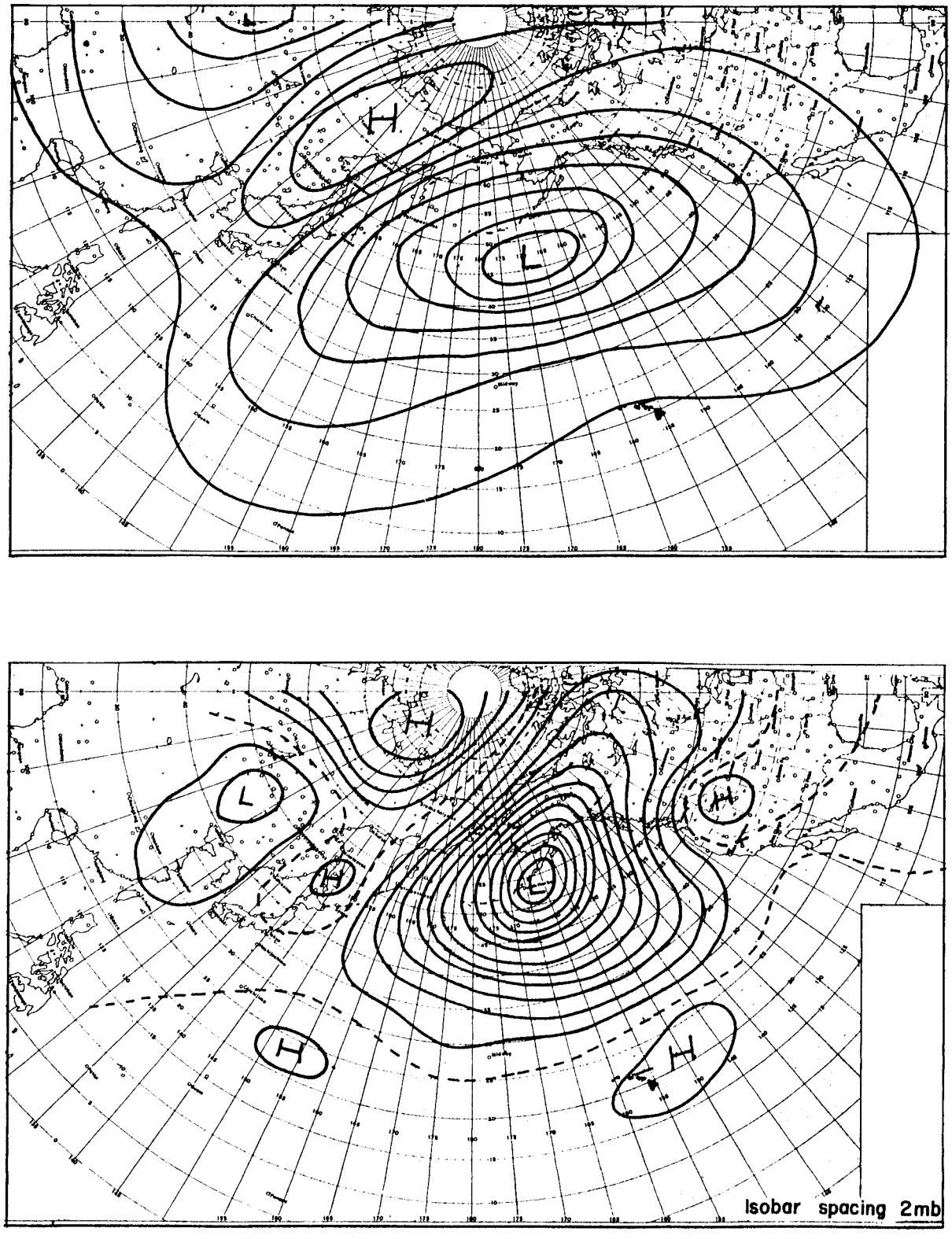
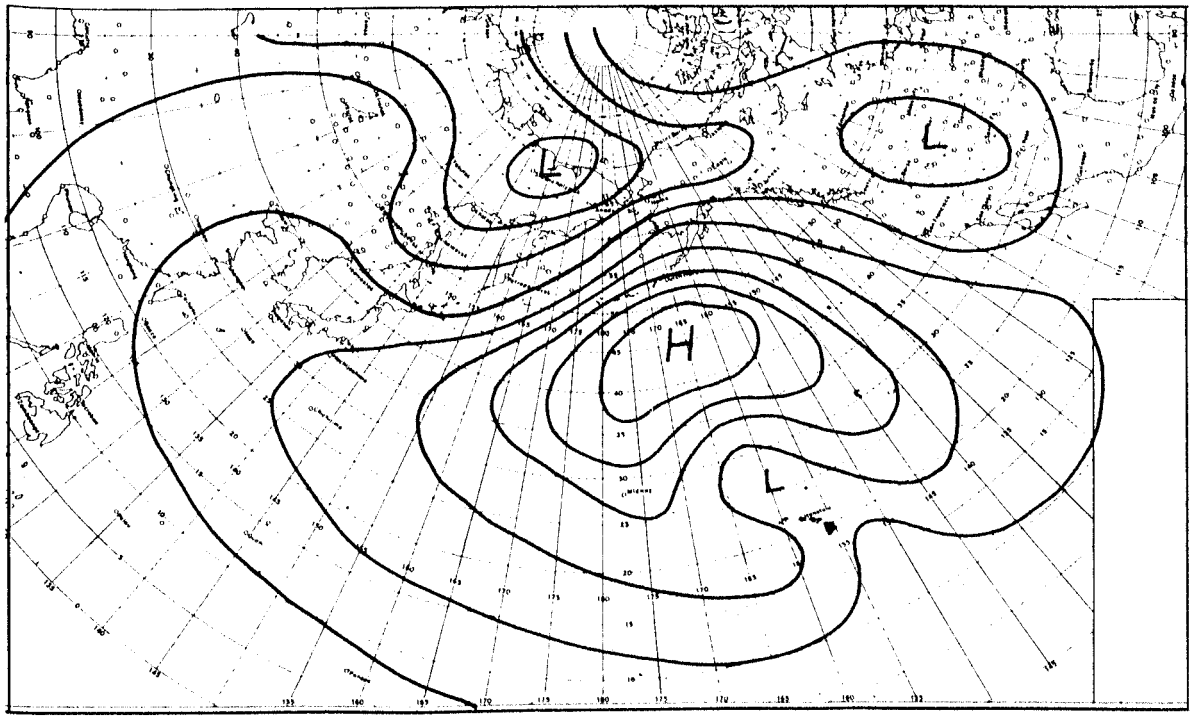


Figure 9. - Composite pressure anomaly chart for general light rain (upper) and observed chart for January 1931 (lower).



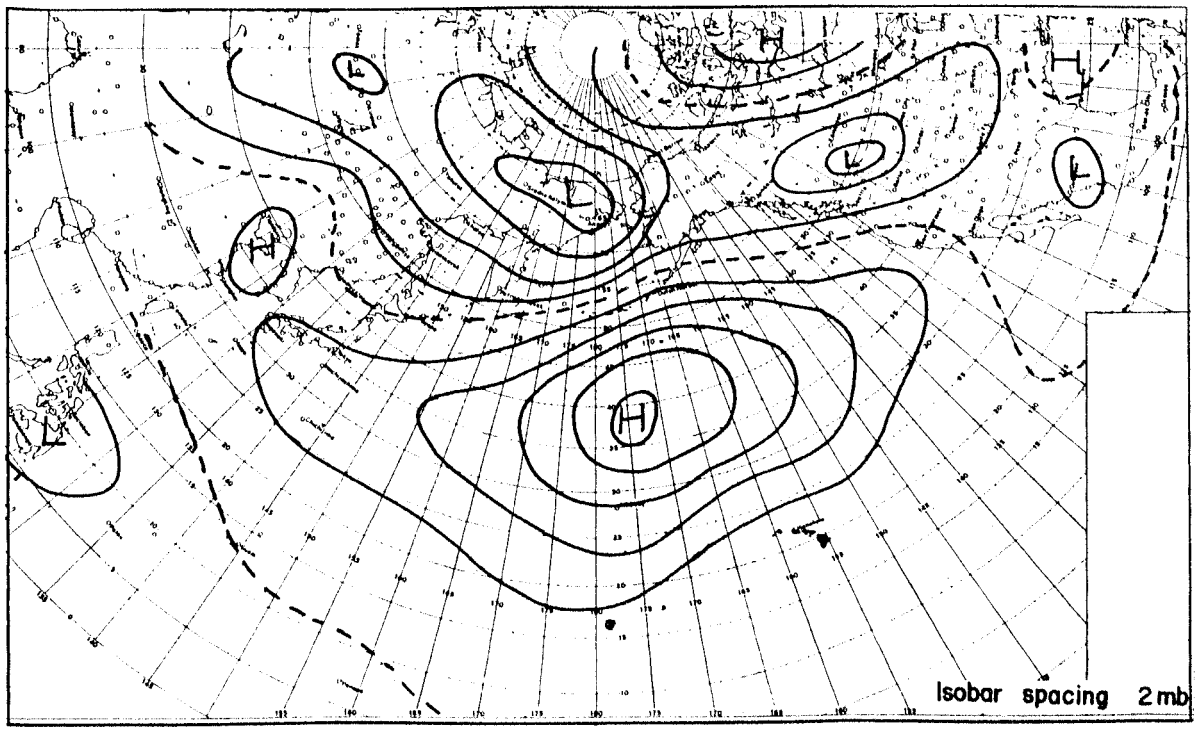


Figure 10. - Composite pressure anomaly chart for general heavy rain (upper) and observed chart for January 1923 (lower).

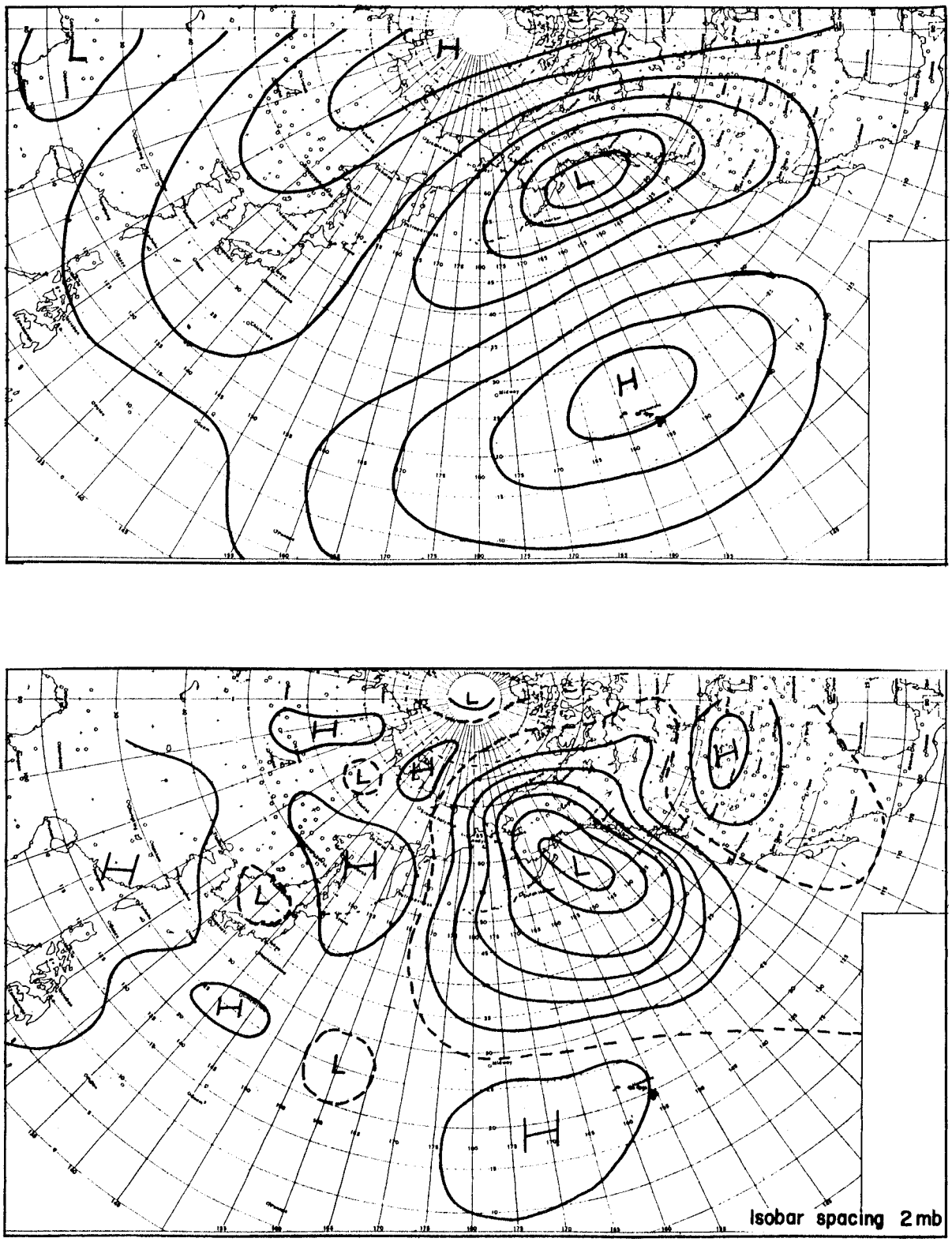


Figure 11. - Composite pressure anomaly chart for light rain at leeward (western) stations (upper) and observed chart for December 1913 (lower).

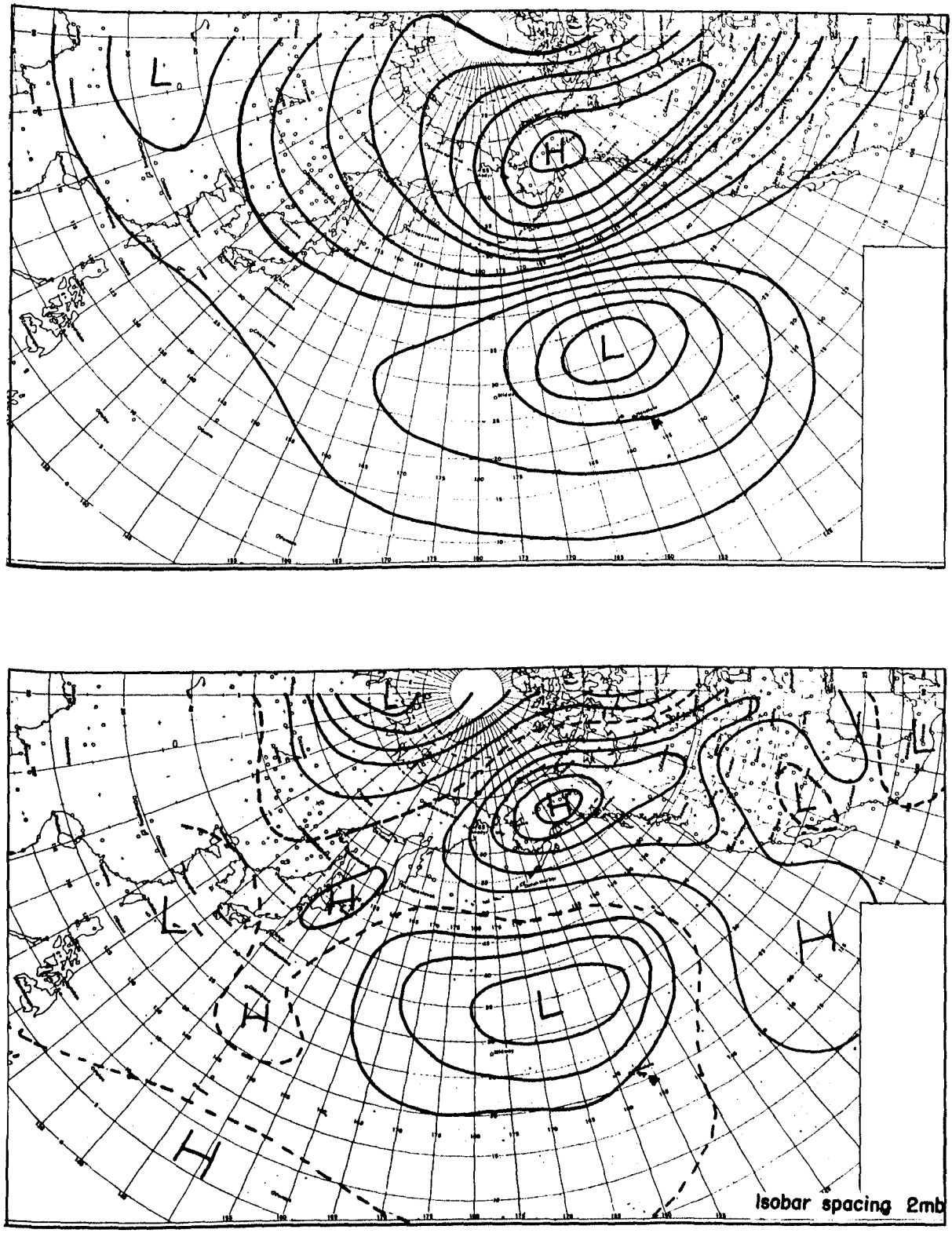


Figure 12. - Composite pressure anomaly chart for heavy rain at leeward (western) stations (upper) and observed chart for December 1933 (lower).

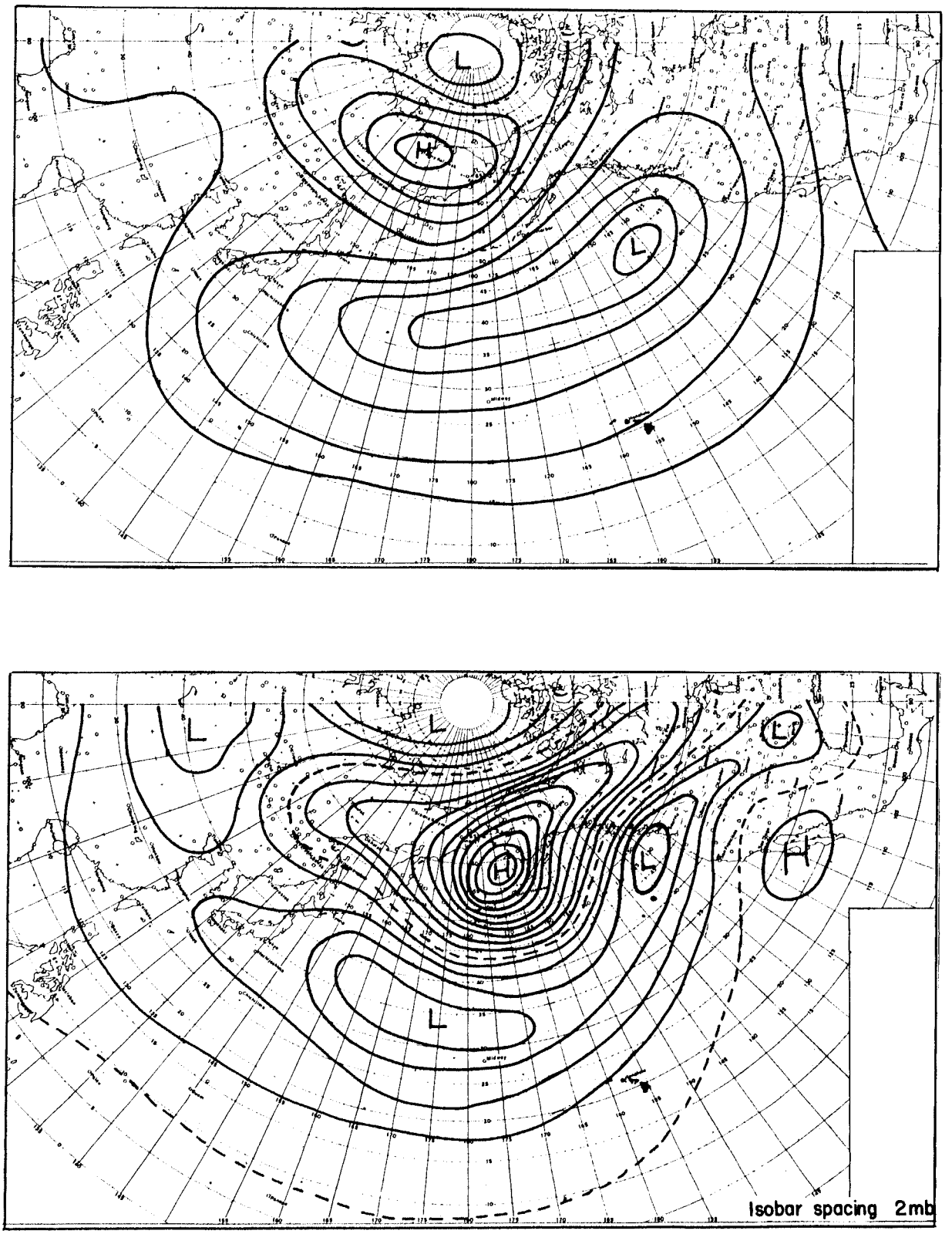
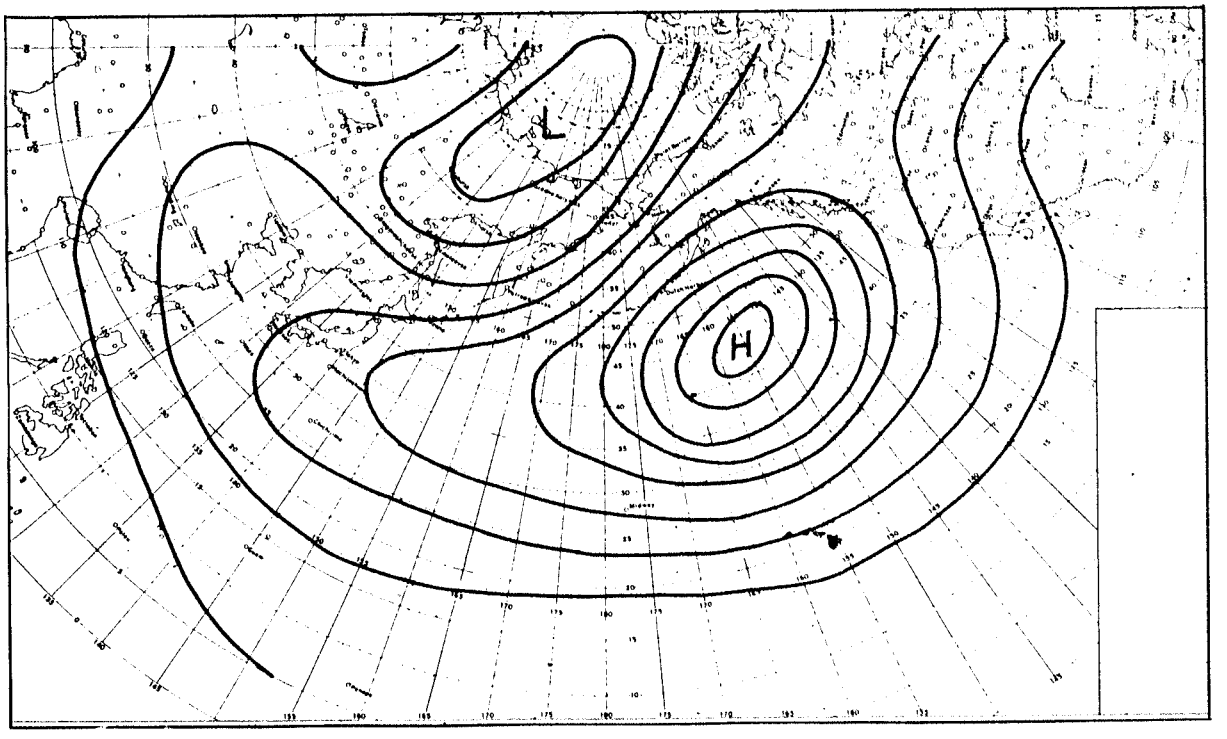


Figure 13. - Composite pressure anomaly chart for light rain on Hawaii (upper) and observed chart for December 1924 (lower).



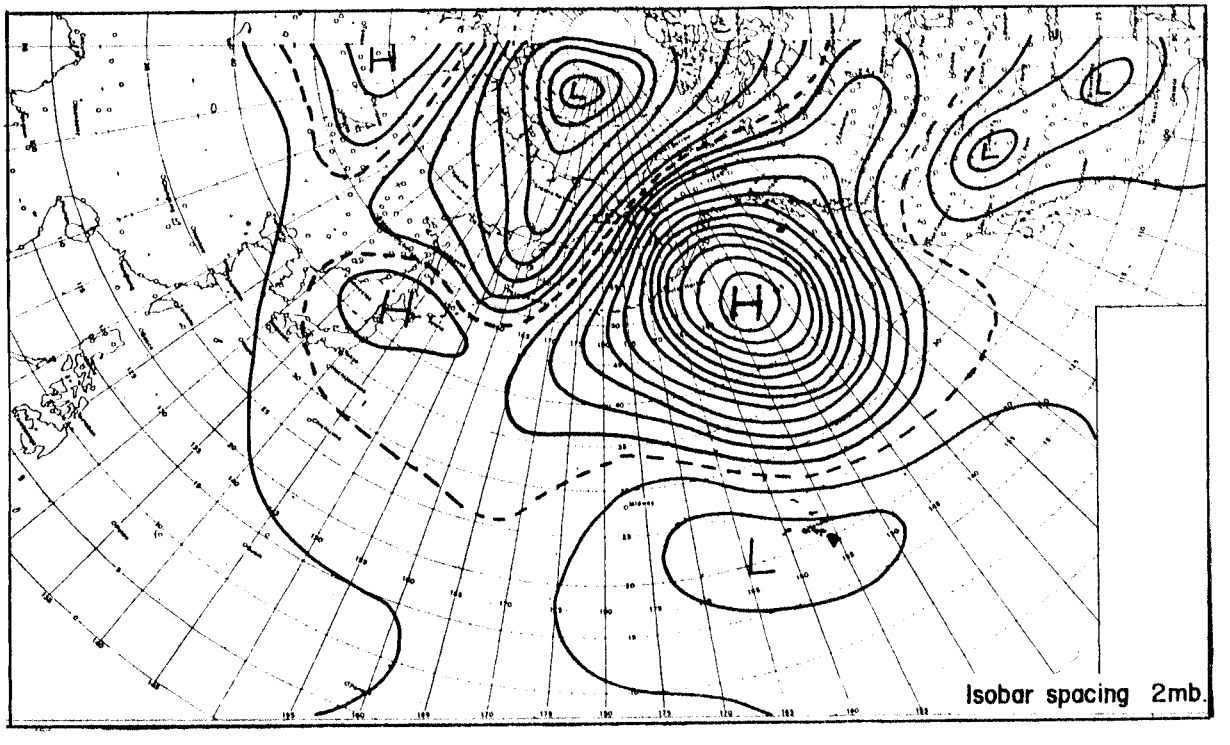


Figure 14. - Composite pressure anomaly chart for heavy rain on Hawaii (upper) and observed chart for January 1937 (lower).

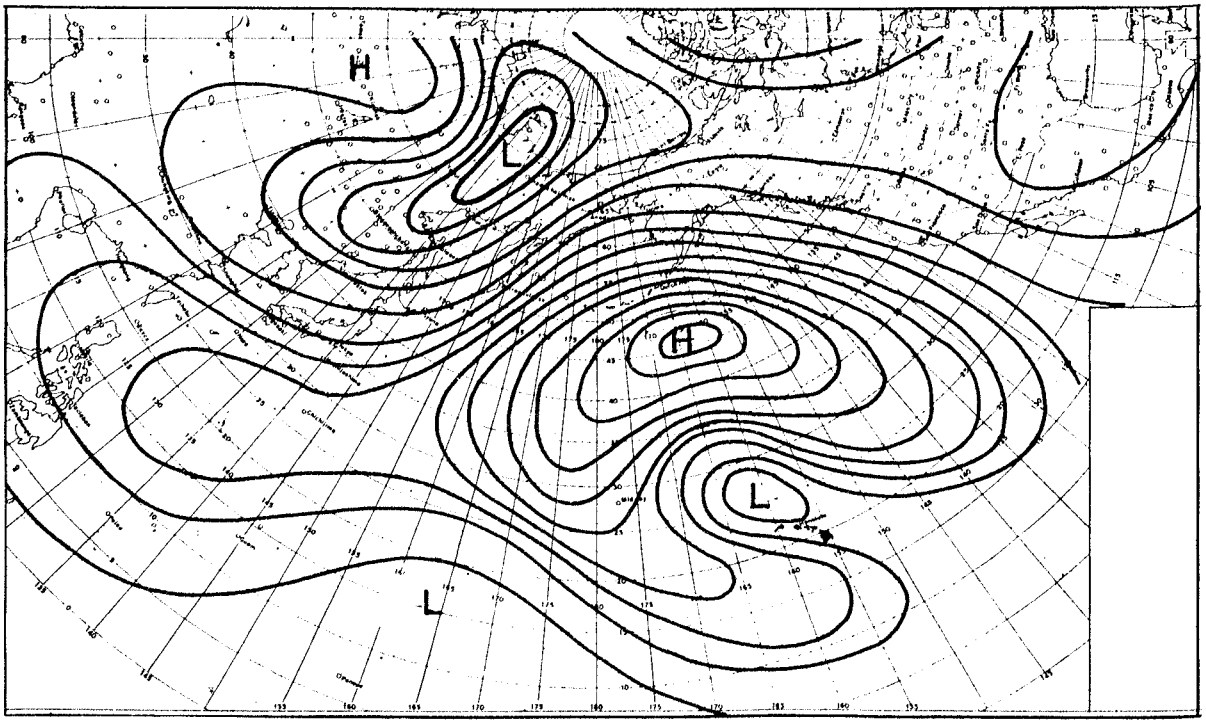


Figure 15. - Ideal pressure anomaly pattern for general heavy rain (reverse of pattern for general light rain).

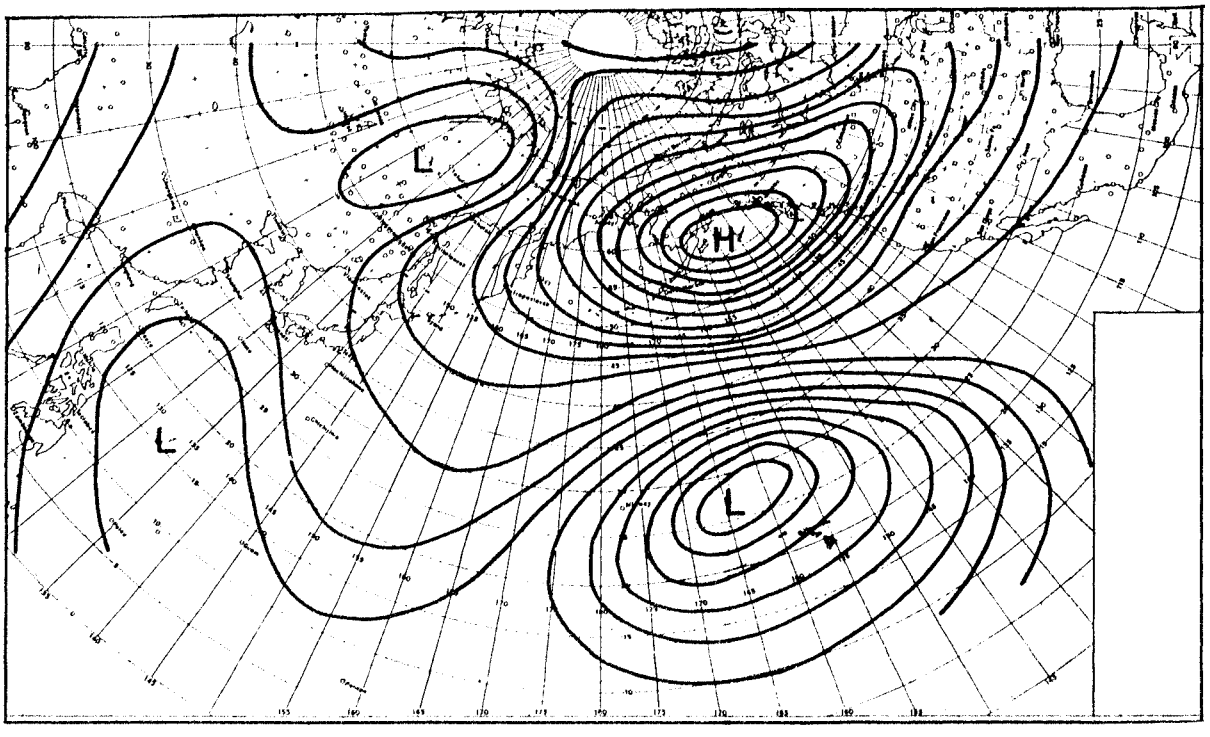


Figure 16. - Ideal pressure anomaly pattern for heavy rain at leeward (western) stations (reverse of pattern for light rain).

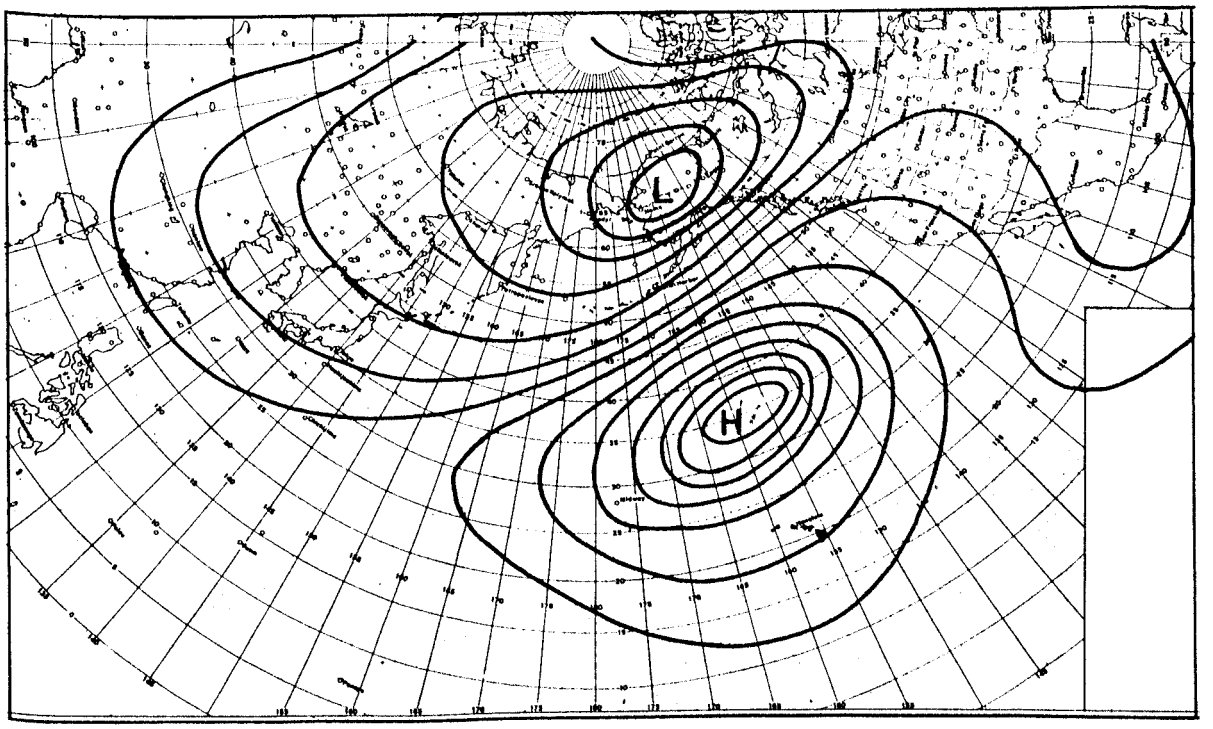


Figure 17. - Ideal pressure anomaly pattern for heavy rain at windward (eastern) stations (reverse of pattern for light rain).

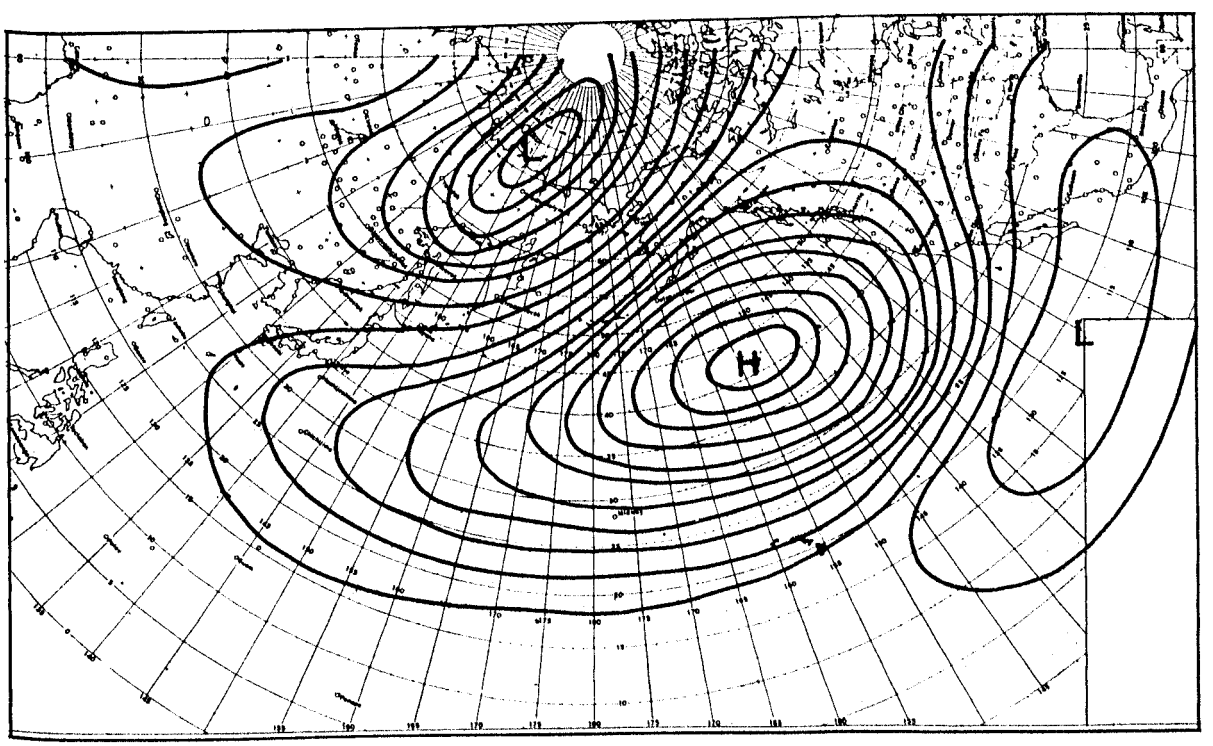


Figure 18. - Ideal pressure anomaly pattern for heavy rain on Hawaii (reverse of pattern for light rain).

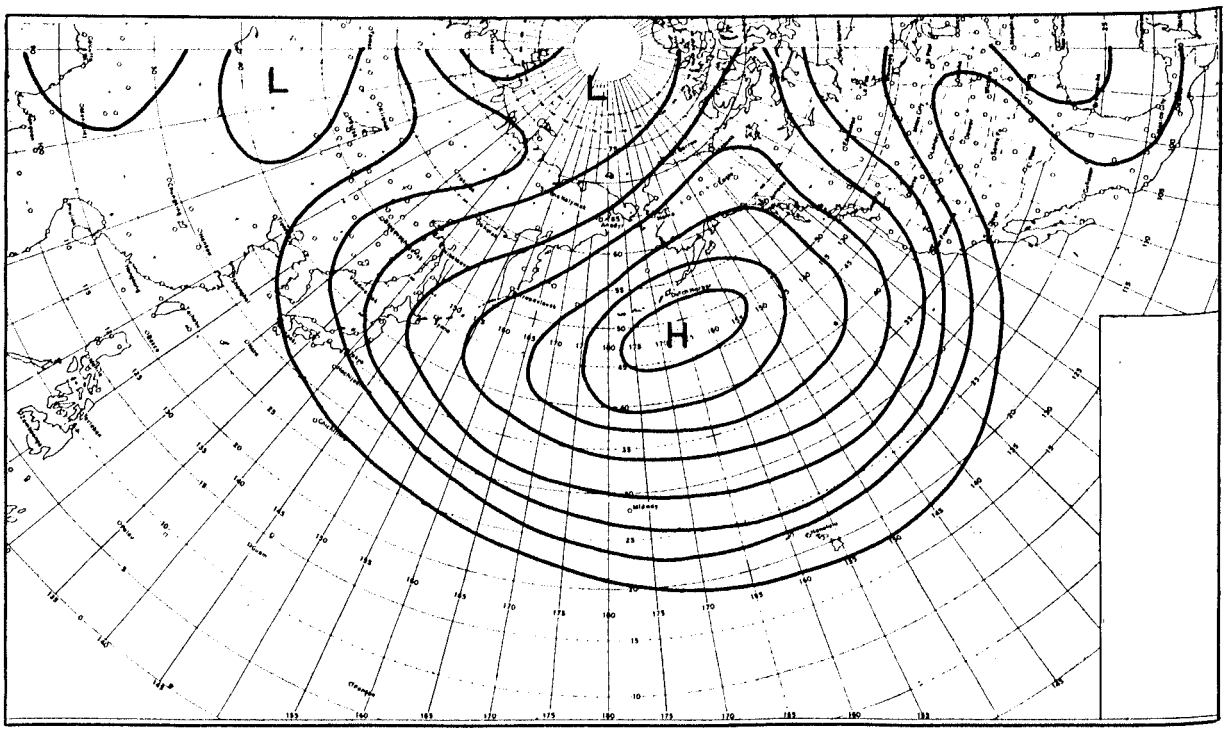


Figure 19. - Ideal pressure anomaly pattern for heavy rain on Oahu (reverse of pattern for light rain).

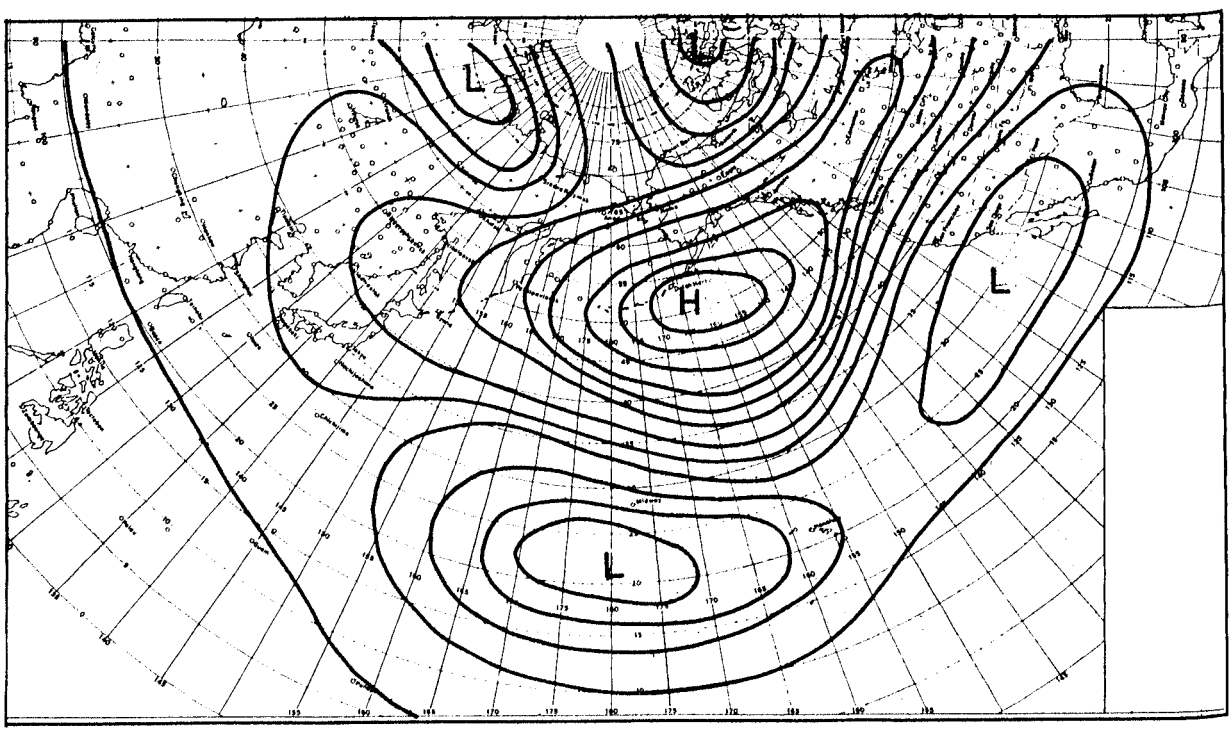


Figure 20. - Ideal pressure anomaly pattern for heavy rain on Kauai (reverse of pattern for light rain).

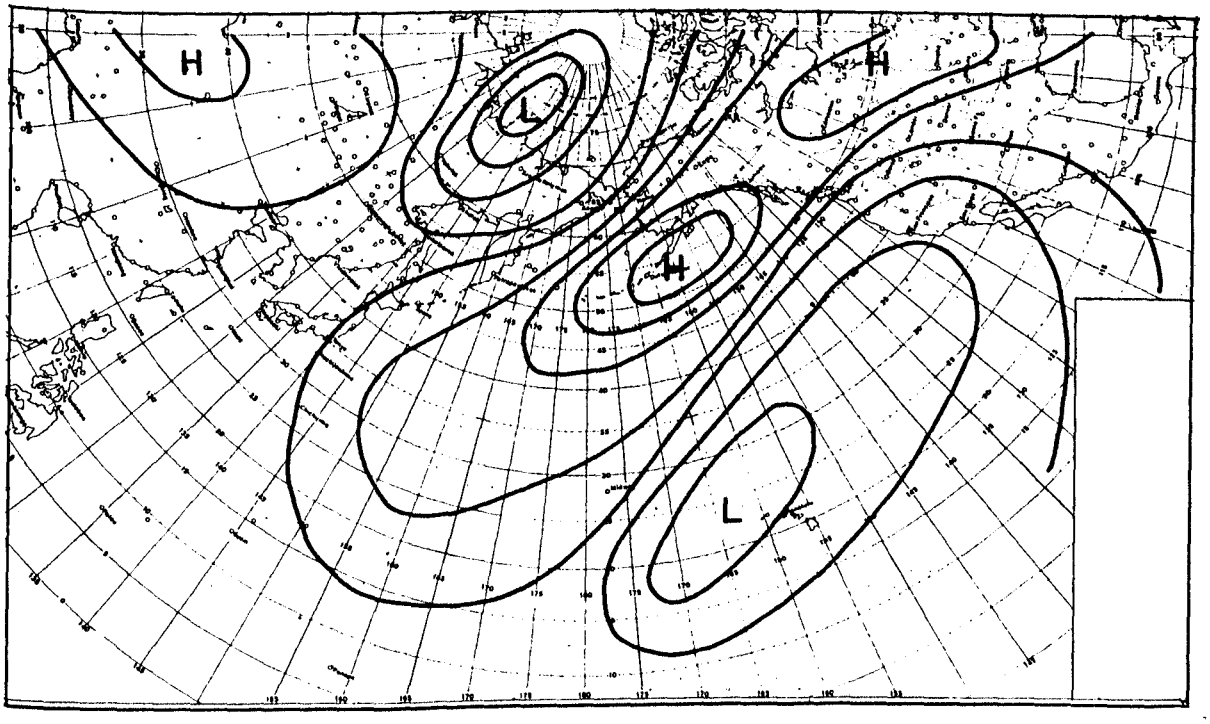


Figure 21. - Ideal pressure anomaly pattern for heavy rain at leeward stations on Hawaii (reverse of pattern for light rain).

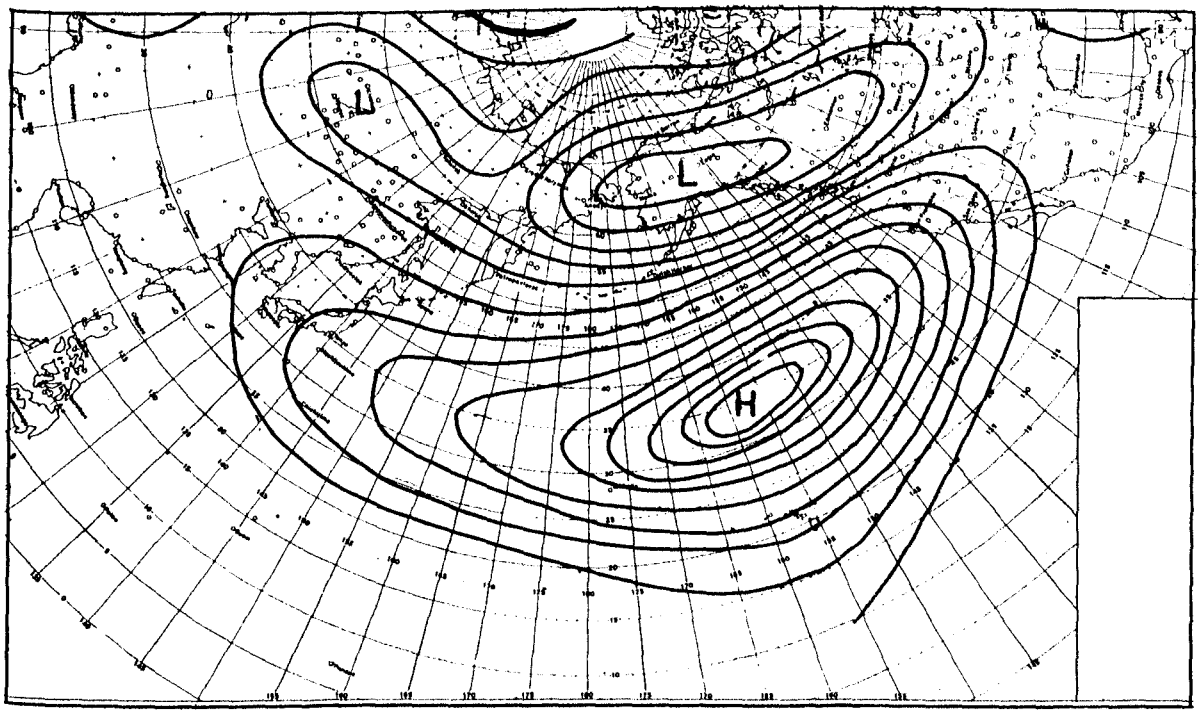


Figure 22. - Ideal pressure anomaly pattern for heavy rain at windward stations on Hawaii (reverse of pattern for light rain).

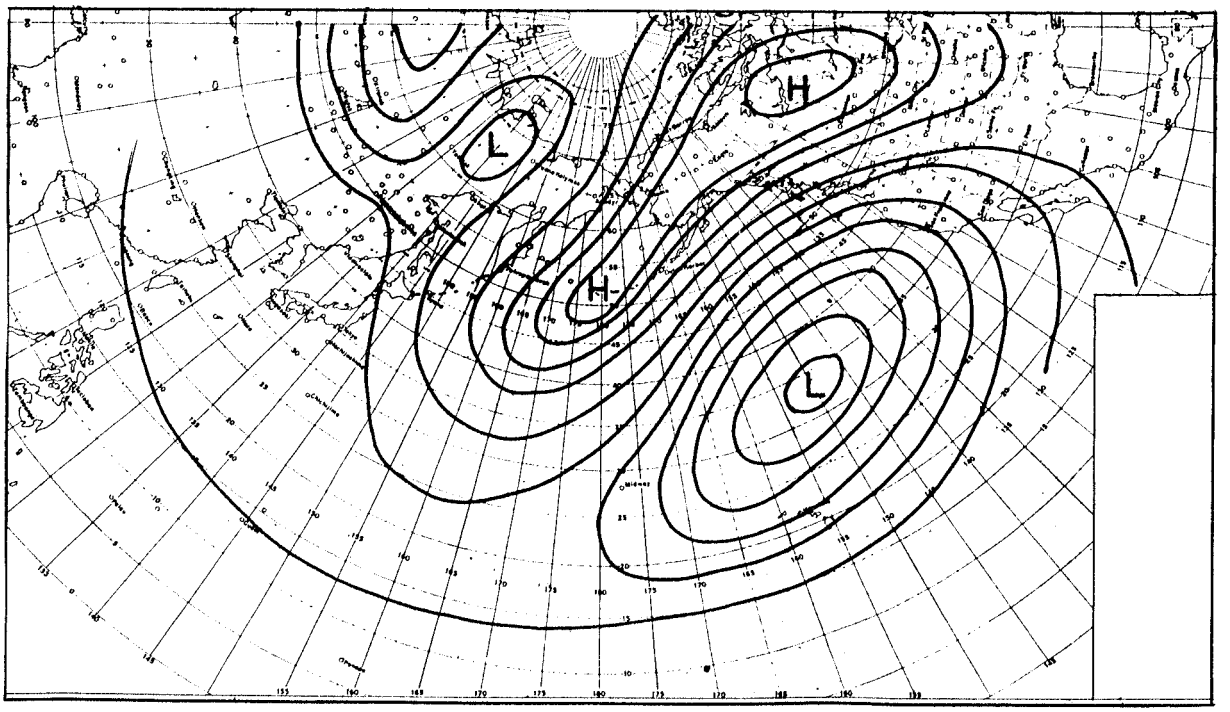


Figure 23. - Ideal pressure anomaly pattern for heavy rain at leeward stations on Oahu (reverse of pattern for light rain).

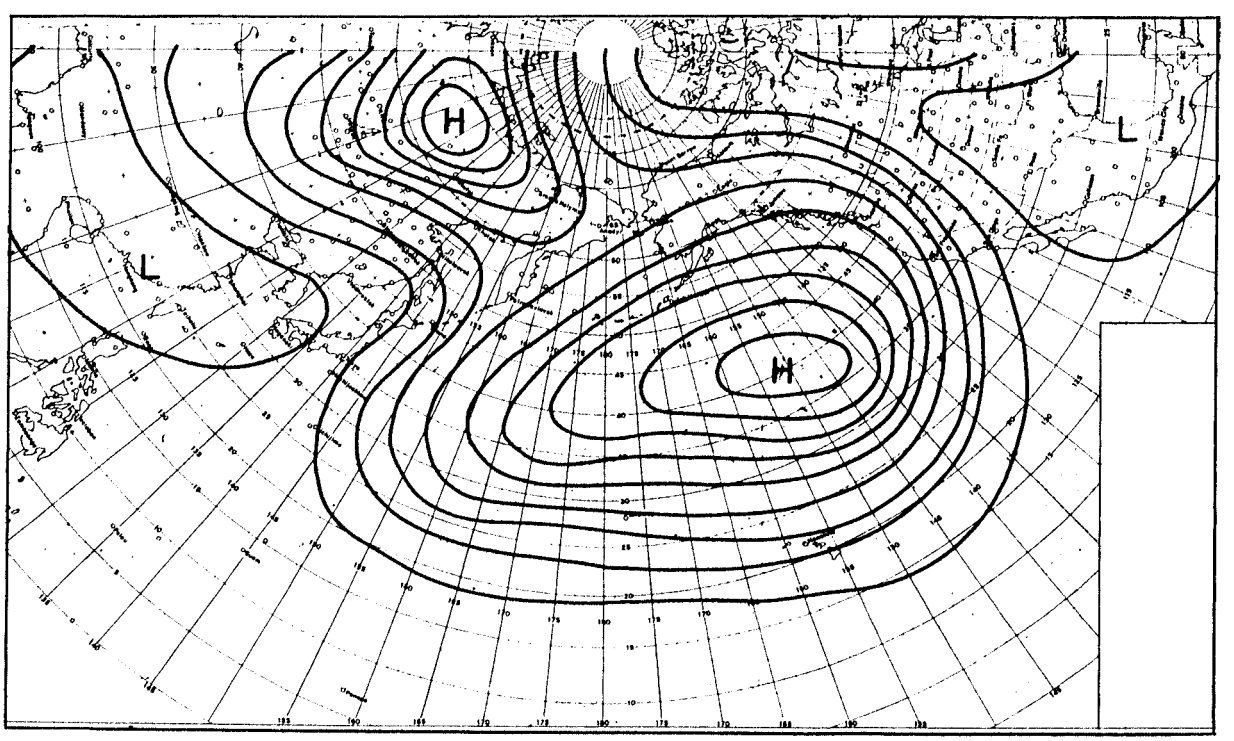


Figure 24. - Ideal pressure anomaly pattern for heavy rain at windward stations on Oahu (reverse of pattern for light rain).

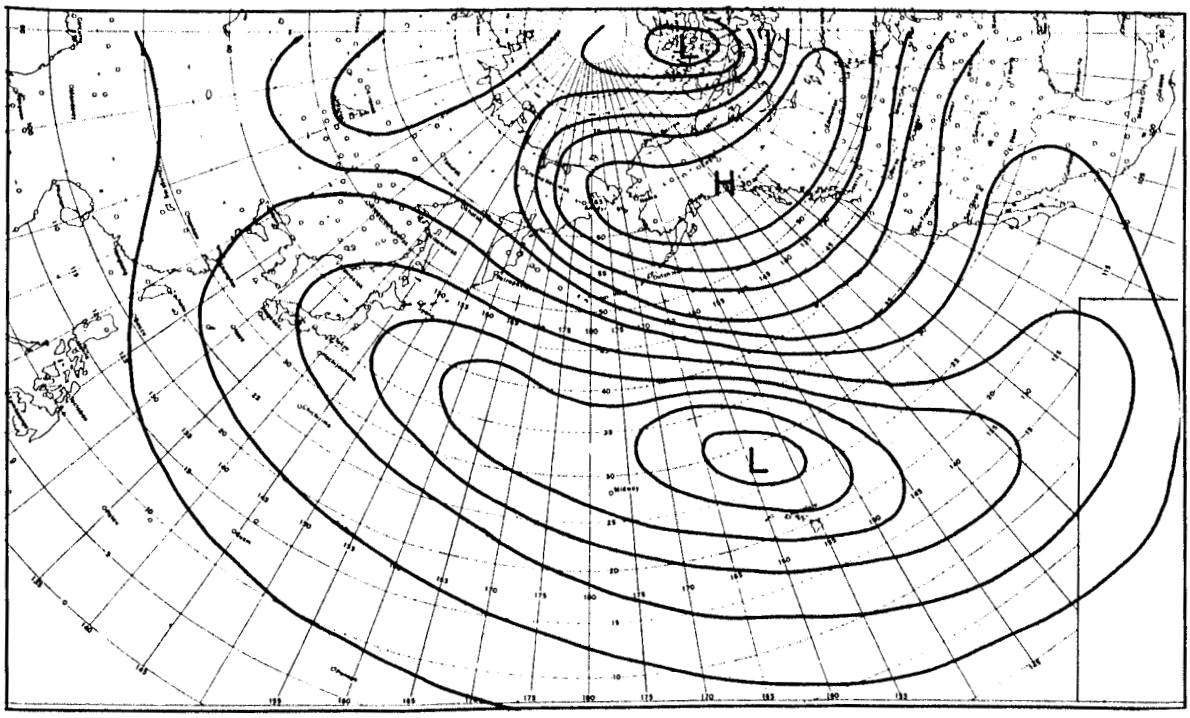


Figure 25. - Ideal pressure anomaly pattern for heavy rain at leeward stations Kauai (reverse of pattern for light rain).

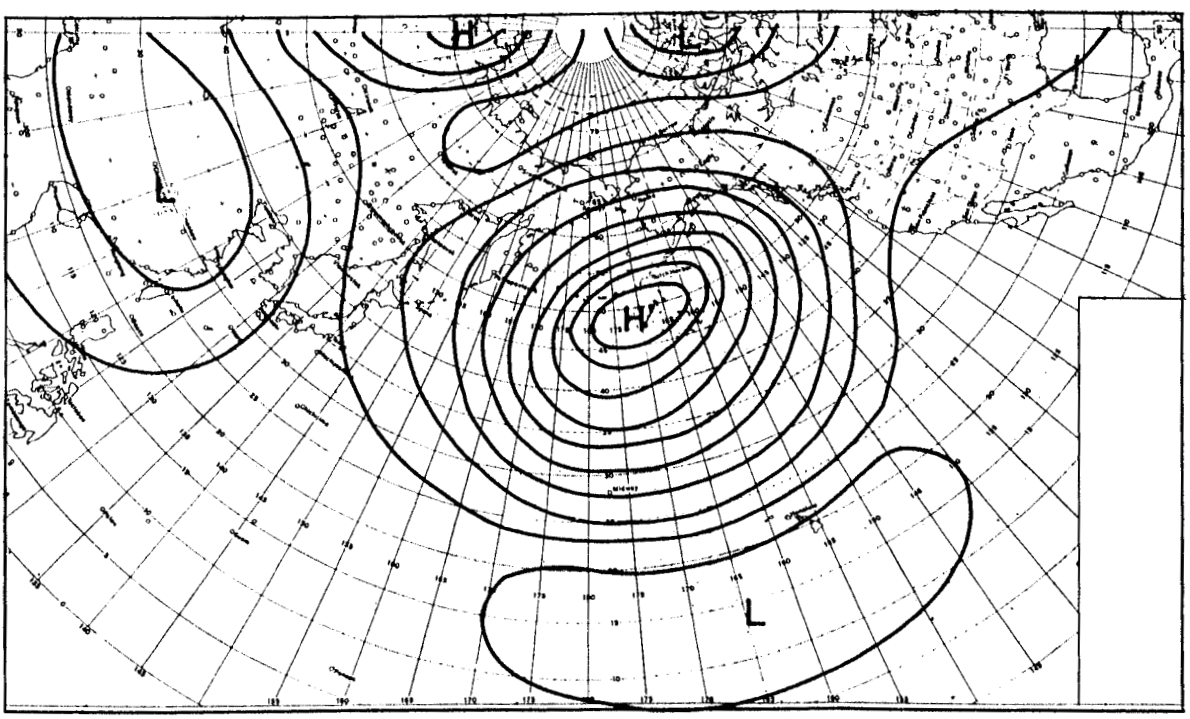


Figure 26. - Ideal pressure anomaly pattern for heavy rain at windward stations on Kauai (reverse of pattern for light rain).

improved that serious attention could be paid to the pressure anomaly patterns. Some thought must therefore be given to the meaning of the anomaly patterns, since the same mean chart may theoretically be composed of an infinite variety of individual patterns.

A pronounced mean monthly anomaly pattern may come about principally as a result of three different processes: (1) a very persistent situation lasting throughout the greater part of the month; (2) a series of similar recurrent situations; (3) a single situation lasting only a few days in an otherwise normal month but in which pressures depart so far from normal that the pattern is impressed on the mean chart. In regions of migratory systems, such as the United States, the recurrent situation may often be the most important for the production of mean monthly anomalies. Examination of a large number of cases of mean monthly anomaly charts related to Hawaiian precipitation, however, leads to the conclusion that, while the first process occurs occasionally, and the second is quite frequent for months of light precipitation, the third process is the most frequent in months of heavy rain in the winter half of the year. Studies by Riehl [5] lead to the same inference.

A logical outcome of the above analysis is that there must exist an inverse relationship between the period of the mean map and the anomaly gradients. This is found to be true for periods up to a month at least. Where a single pronounced pattern of short duration is strongly reflected in the mean monthly pattern, it follows that the synoptic mean patterns will resemble each other but that the gradients on the synoptic chart will be much greater. This principle can be used to gain a clearer insight into the meaning of the ideal patterns by translating them into synoptic pressure patterns. The first step in this process was to preserve the anomaly pattern but to adjust the anomaly values to those appropriate to a daily synoptic chart. Since it is much easier to visualize atmospheric processes in terms of total flow, the normal pressures for the month of January were added to the adjusted anomalies and isobars drawn. Since the normal pressure patterns in this region are very similar for all winter months these charts may then be considered as typical winter patterns. The result is what might be considered a set of idealized synoptic pressure patterns representative of the various types of rainfall regimes. As can be seen in figures 27 to 34 and from the discussion to follow, eight of these charts can be arranged in a series with a regular gradation of patterns, whereas the remaining two (figs. 35 and 36) are special patterns. (The Oahu rainfall regime has been shown to be intermediate between those of Kauai and Hawaii and therefore the Oahu charts are not included.) Since the same adjustment was applied to each original chart, and the same normal pressures were added to each, it is evident that the gradations are inherent in the original charts. The isobars have not been labeled because again we are primarily concerned with the flow patterns. Although a great deal of work remains to be done before the significance of the patterns can be fully established, in the discussion that follows each pattern will be qualitatively described and some tentative explanations of the associated rainfall patterns will be offered.

1. Heavy Rain - Hawaii: wave in a broad easterly current. Figure 27. The subtropical ridge line is displaced far to the north at the longitude of the Hawaiian Islands. The Islands are imbedded in a broad tropical stream. This type of circulation becomes perturbed and easterly waves are generated. Heavy rain is experienced on the windward slopes of all the islands and as the wave progresses westward, the southerly wind component produces precipitation on the leeward sides of the islands. The rainfall may be quite heavy at the southern end of the chain where the wave activity is most intense, but decreases rapidly northward where the wave becomes damped. The result is a stratification with heavy rain to the south.

2. Heavy Rain - Windward: strong trade winds. Figure 28. The subtropical ridge line is now somewhat farther south than in the previous pattern. The tropical easterlies are not quite so broad and wave activity is absent in the vicinity of the Islands. Upslope winds produce heavy rain on the windward sides of all the islands but precipitation is moderately light on the leeward sides. The trade-wind inversion is very pronounced so that the rainfall is strongly orographic.

3. Light Rain - Leeward: Moderate trade winds. Figure 29. The subtropical ridge line is now quite far south, and the easterlies are much less intense. The rainfall is moderate on the windward sides of the islands, but very light on the leeward sides.

4. Light Rain - Kauai: weak easterlies. Figure 30. The ridge line is now just north of the Islands. The easterly current is very weak and the trade-wind inversion very pronounced. Some orographic precipitation occurs on the windward slopes of the southernmost islands, but the circulation decreases northward so that the island of Kauai remains dry.

5. General Drought: Light variable winds. Figure 31. The subtropical ridge is directly over the Hawaiian Islands. The air aloft is extremely stable, and the winds are local. Little if any precipitation falls at any station. This situation

may persist for long periods, with slight fluctuations in the ridge line which produce light precipitation stratified northward or southward, depending on the direction of the drift of the anticyclonic cell.

6. Light Rain - Hawaii: weak westerlies. Figure 32. The subtropical ridge has now retreated southward and the region is under the influence of weak polar westerlies. Here we have the complement of pattern 4 (fig. 30) inasmuch as the westerly circulation decreases southward, so that some rain is experienced on the leeward (i.e. with respect to the northeast trades) sides of the northern islands but the southernmost islands remain very dry.

7. Light Rain - Windward: moderate "Kona". Figure 33. The polar trough is now well south of its normal position. Upslope winds on the leeward sides of the Islands produce considerable precipitation in what is known locally as a "Kona" storm. The convergence produced by the cyclonic circulation tends to cause some precipitation in the other regions, but not enough to overcome the effect of downslope flow on the windward sides of the islands. Hence, the stratification of light rain on the windward (eastern) sides of the Islands.

8. Heavy Rain - Leeward: strong "Kona". Figure 34. The center of the polar trough is now just north of the Islands. Convergence associated with the cyclonic circulation produces moderately heavy precipitation even on the eastern sides of the Islands but the strong orographic upslope winds on the western slopes are responsible for extremely heavy precipitation. In certain cases when the circulation is very intense this type of storm may result in heavy rain at all stations.

The two remaining map types (figs. 35 and 36) do not belong in the above series, but are special patterns.

9. General Heavy Rain. Figure 35. This is the pattern referred to by Riehl [14] as universally associated with extremely heavy precipitation in the tropics. He describes it as a polar trough superimposed on a low-latitude trough. The circulation above the easterly wave is westerly, and it has been suggested that in some cases the low-latitude trough may actually progress eastward, being steered by the polar trough aloft. However, normally the blocking ridge to the east is so pronounced that both the upper and lower troughs are translated westward. Added to the great rain-producing potentialities of this type of storm are the upslope wind components that occur successively on the windward and leeward portions of the island, and produce record breaking falls of rain at many stations. The development of this pattern and its associated rainfall pattern has been studied in great detail, and this particular chart is actually a composite of ten carefully selected individual synoptic patterns. The composite precipitation patterns, expressed in percentiles, were investigated. On the island of Hawaii, which is well exposed to upslope winds on all sides, the center of heavy precipitation is first observed on the northwest side of the island in the Hamakua district and gradually rotates anticyclonically as the wave progresses through the Hilo, Puna, Kau, Kona, and the west side of Kohala regions. On Oahu which has two parallel mountain ranges oriented NW-SE, the heavy-rain center does not rotate but shifts from the Koolau (windward) range to the Waiamea (leeward) range in conjunction with the shift from northeast to southeast winds.

A curious phenomenon is the appearance on the composite of a series of waves around the hemisphere averaging about fifty degrees in wave length. That this is more than a statistical fiction is evident by the fact that some of these are much deeper and more pronounced than the one over the Hawaiian Islands.

10. Heavy Rain - Kauai: southeasterly flow. Figure 36. Of all the patterns which have been presented this is perhaps the most complex and difficult to explain. Clearly much more information is needed before this storm type can be fully described. It is evident that this is an extreme example of meridional flow with a very low zonal index. The strong ridge in the eastern Pacific presents a barrier to the eastward progress of polar troughs. It is well known (e.g. [2] and [15]) that in such cases cyclonic systems tend to be displaced far south of their normal trajectories. To the west of the trough cold polar air is carried to low latitudes, and on the eastern side warm moist tropical air is transported northward. The juxtaposition within a narrow band of air masses of such markedly different densities, results in a concentration of vertical motions. The isentropic surfaces in the troposphere, with their associated cloud systems must lower to a minimum as the air flows southward around the eastern ridge, and rise rapidly as the air is transported northward at the western edge of the ridge. Heavy precipitation would begin some distance north of the initial rise when the convective instability of the air mass has been realized. Detailed study of a number of examples shows that this type of storm usually lasts about two days. Extremely heavy rain is experienced on Kauai the first day, and the heavy rain progresses southward to Oahu, Maui, and lastly to Hawaii. Sometimes, however, the rain never reaches the southern end of the chain. Even when heavy precipitation does extend to Hawaii on the second day it is confined mostly to

the Puna and Kau (southern) districts of the island, and is usually very light in the Kohala (northern) district. This type of storm produces winds which are in general parallel to the ridges, and is thus the purest example of rainfall which is independent of the orographic effect. The general geographic stratification is produced by the storm circulation, but even here we observe a strong tendency toward a secondary stratification dependent on the added effect of orographic winds.

In spite of the seasonal variation of the normal pressure patterns, the same general types of anomaly patterns are related to rainfall stratification in summer as in winter. In midsummer the Islands are in the relatively broad belt of easterlies, and general westerly flow is absent. It is evident, then, that an anomaly trough in the region of the Pacific anticyclone in summer represents not a westerly but a weakened easterly circulation whereas an anomaly ridge still represents a strong easterly circulation. This accounts for the summer-rainfall secondary maximum at windward stations in contrast to the annual minimum at leeward stations (fig. 5). The weaker the easterlies, the stronger is the sea-breeze rainfall on the leeward slopes [6]. Latitudinal stratification is now not so much a function of the shifts of the center of the Pacific anticyclone as of fluctuations of the intensity of the center, which produce latitudinal shear in the trade winds. General heavy rain results from intense easterly waves.

It has been seen that the latitudinal shift of the system comprising the subtropical ridge and polar trough is a sensitive index of both the wind velocity and horizontal shear. Two implications are here involved: (1) since at low latitudes the variability of pressure decreases rapidly with decreasing latitude, a considerable rise or fall in pressure to the north is associated respectively, with strengthening of the easterlies (weakening of the westerlies), or strengthening of the westerlies (weakening of the easterlies); (2) at reasonable distances from the centers wind velocities increase outward from anticyclones and decrease outward from cyclones. As a consequence, the position of the systems with respect to the island serves as an index of wind shear.

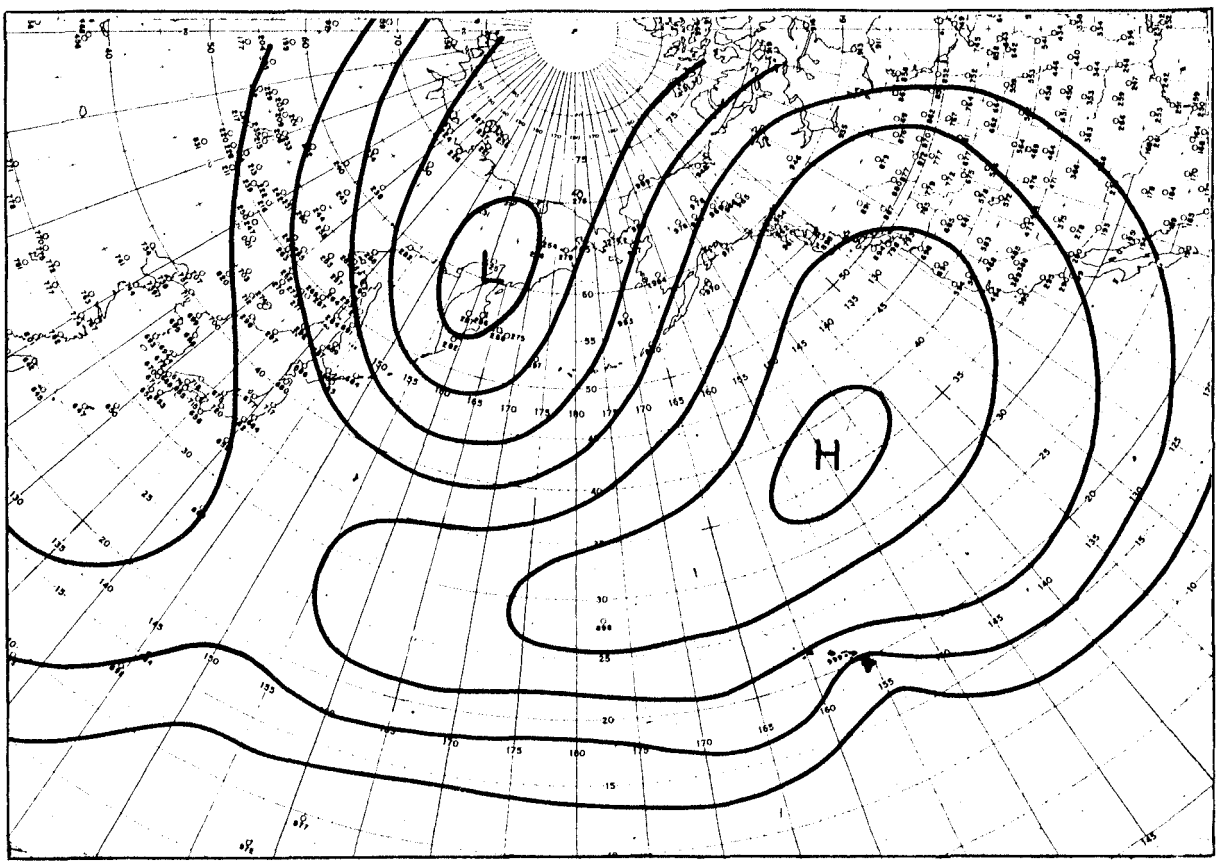


Figure 27. - Ideal pressure pattern for heavy rain on Hawaii.

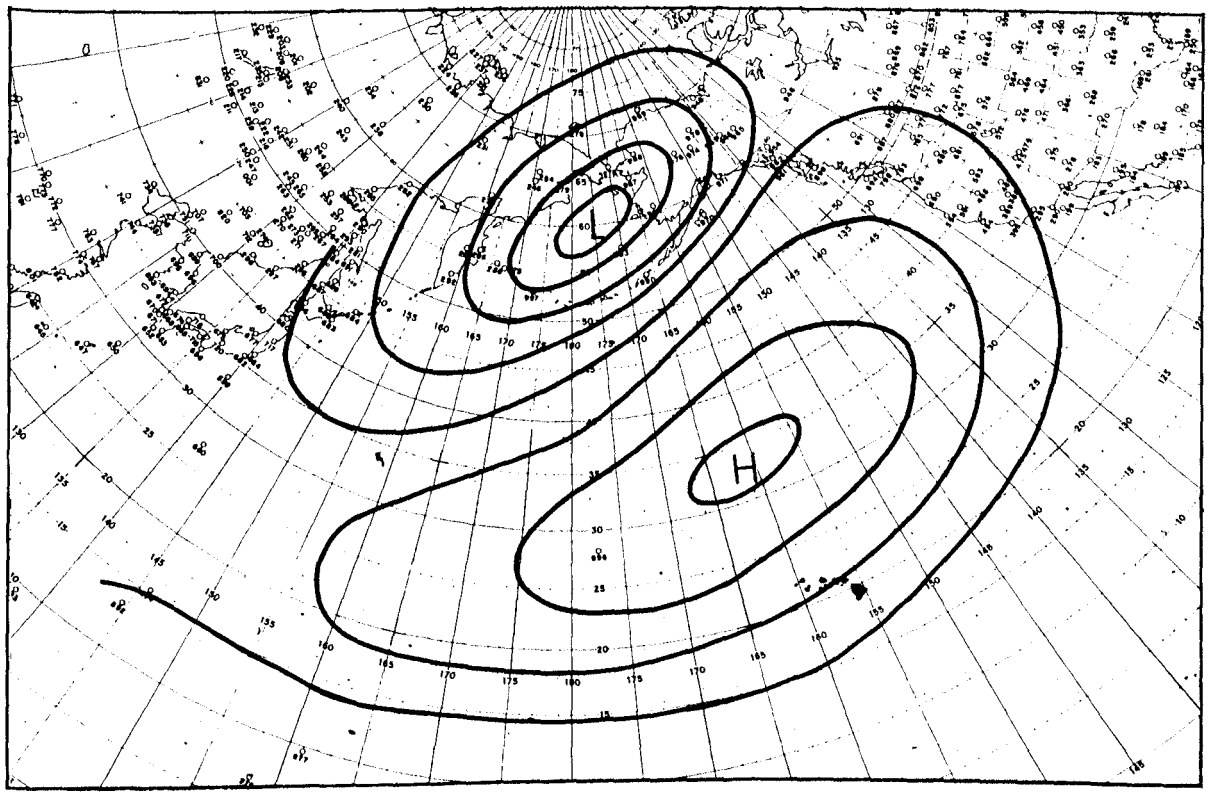


Figure 28. - Ideal pressure pattern for heavy rain at windward stations.

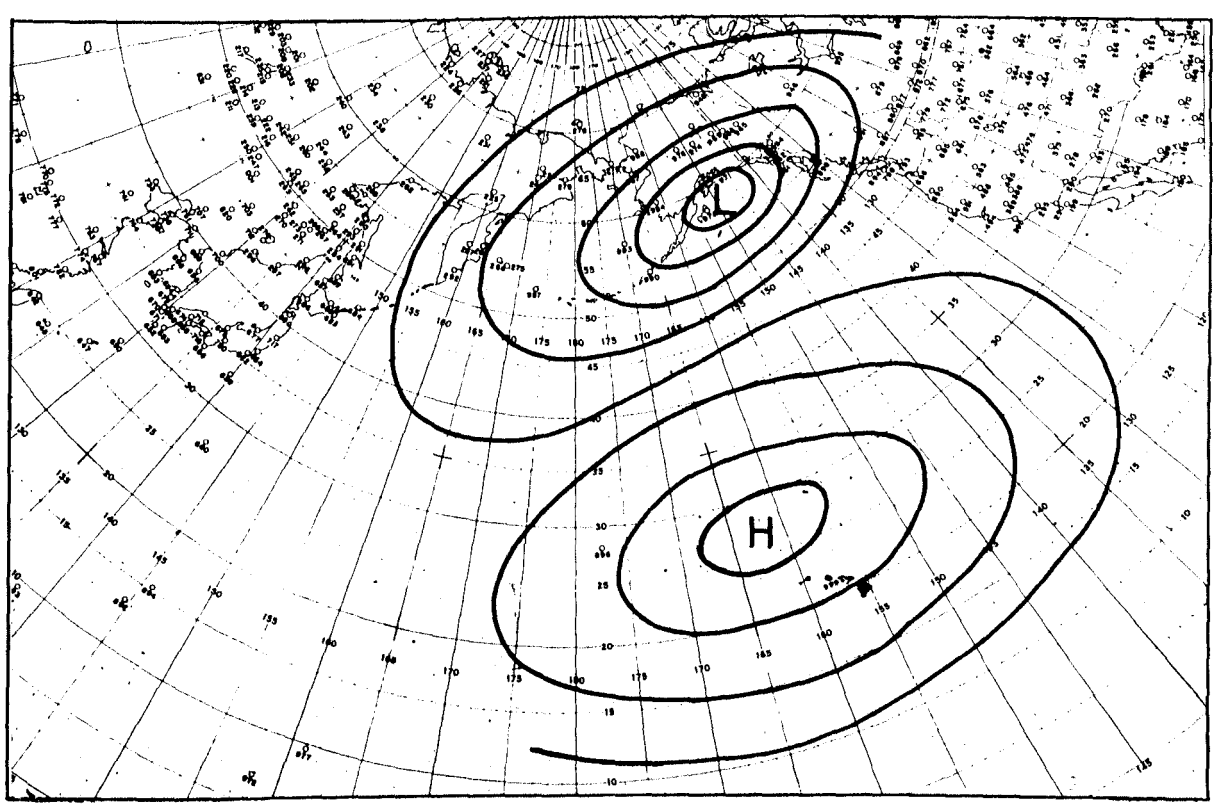


Figure 29. - Ideal pressure pattern for light rain at leeward stations.

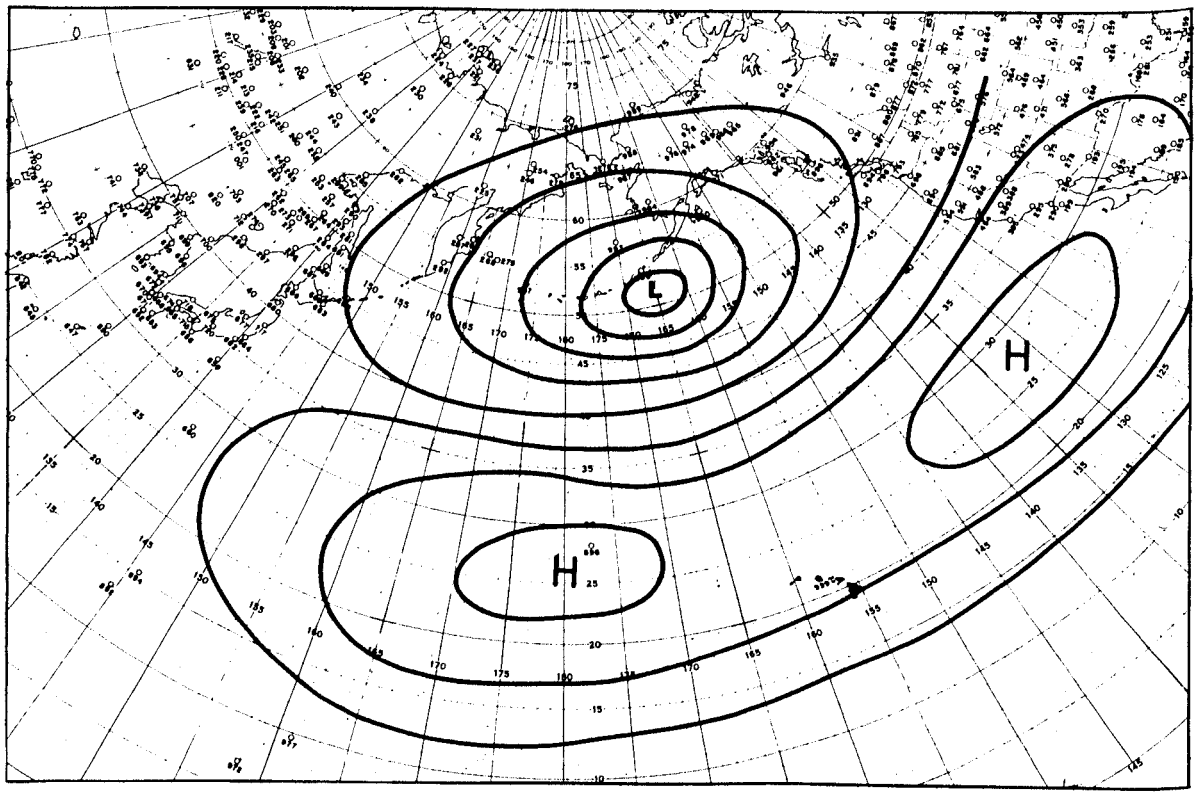


Figure 30. - Ideal pressure pattern for light rain on Kauai.

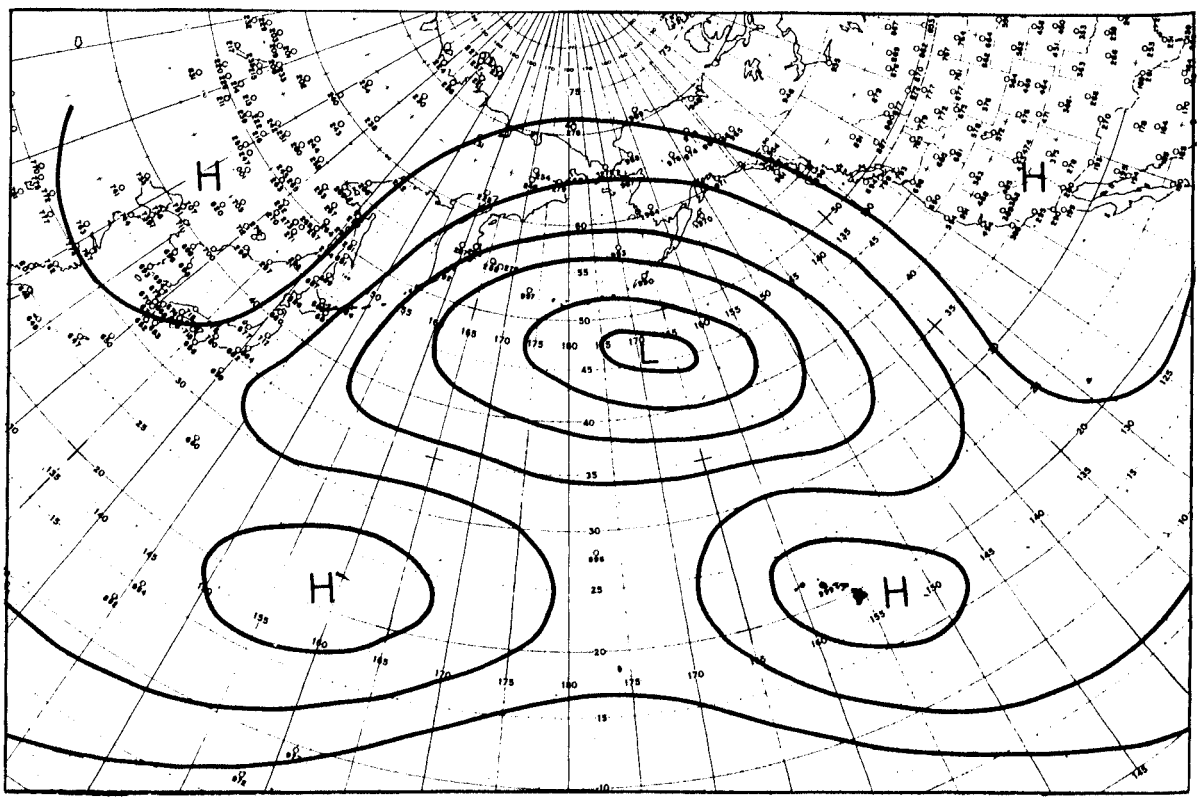


Figure 31. - Ideal pressure pattern for general drought.

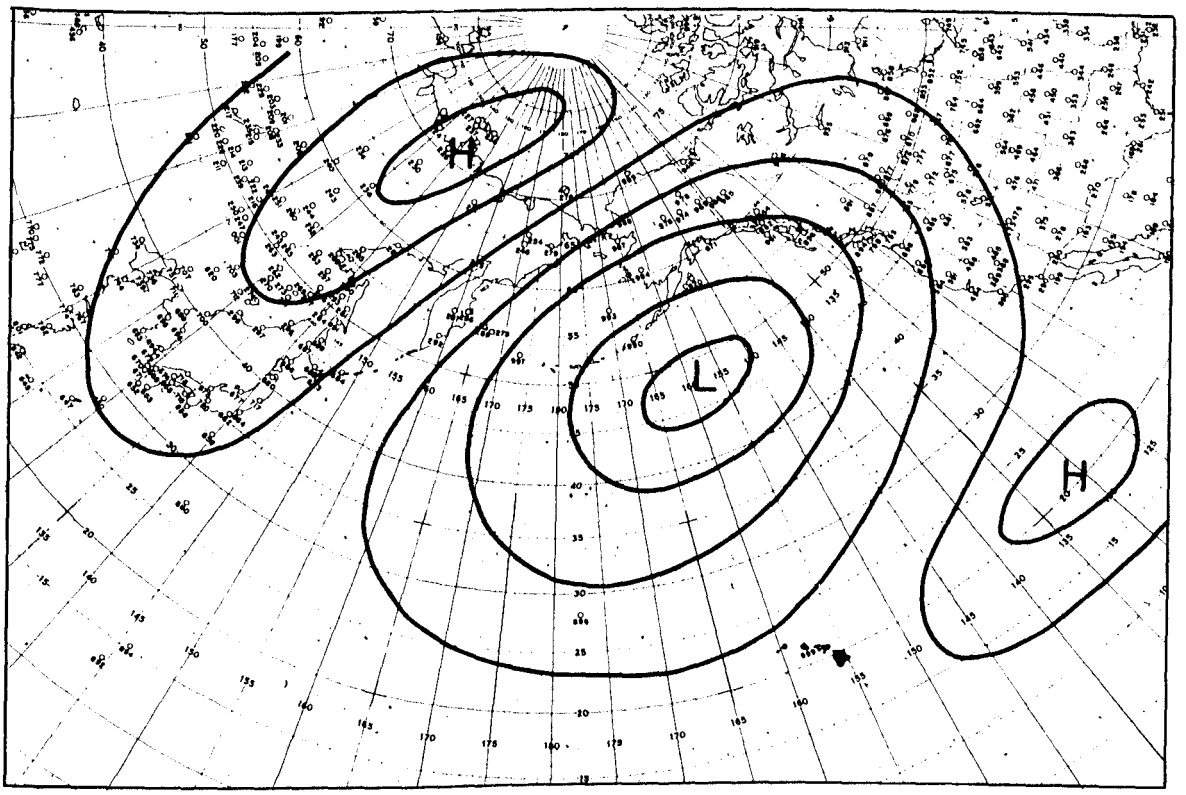


Figure 32. - Ideal pressure pattern for light rain on Hawaii.

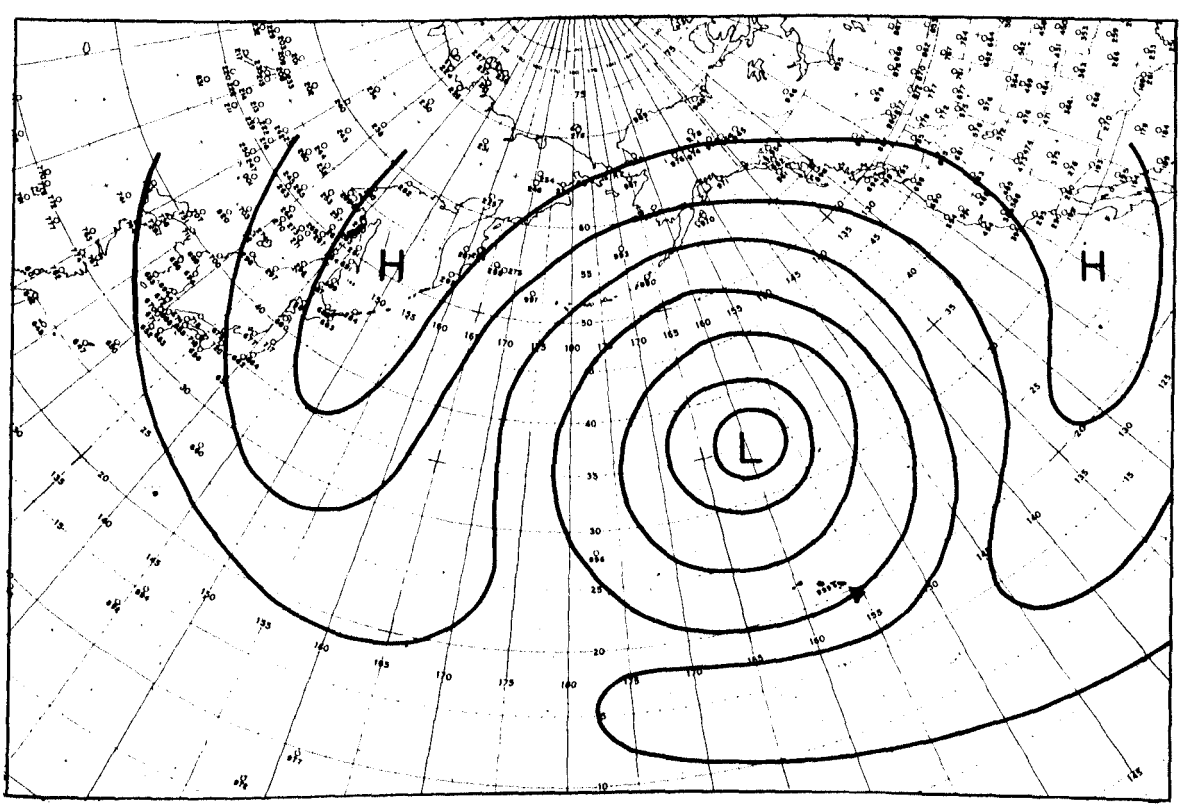


Figure 33. - Ideal pressure pattern for light rain at windward stations.

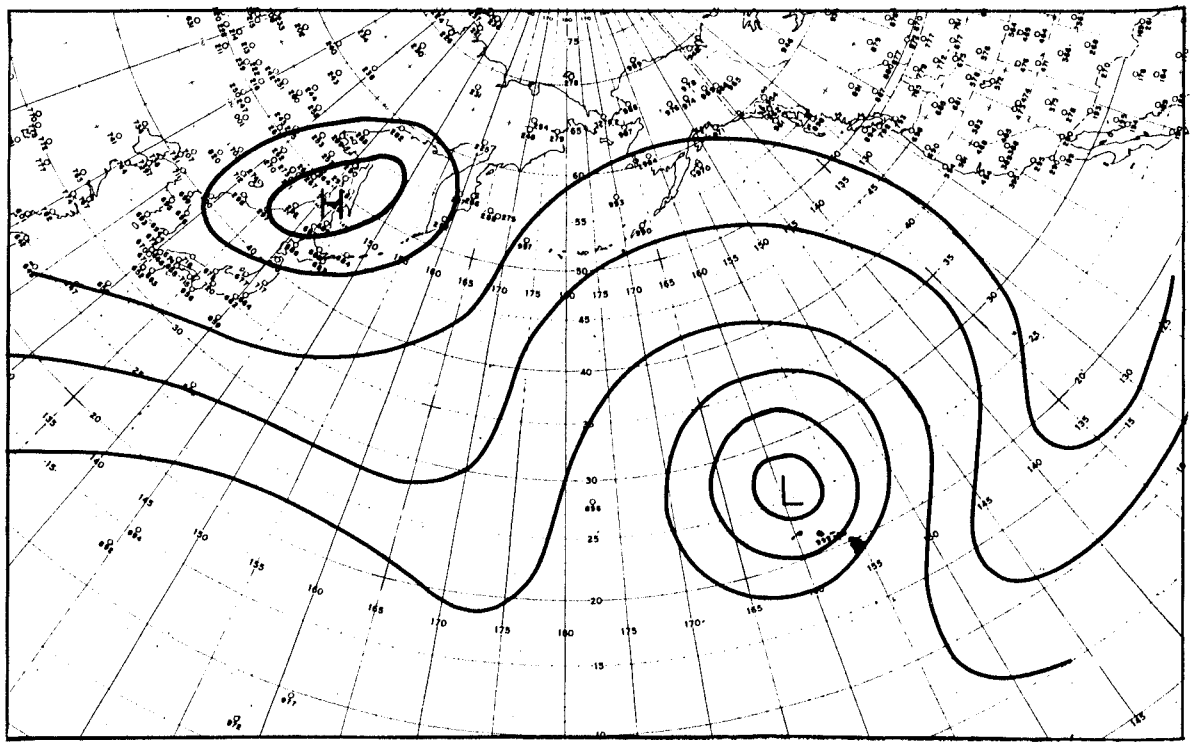


Figure 34. - Ideal pressure pattern for heavy rain at leeward stations.

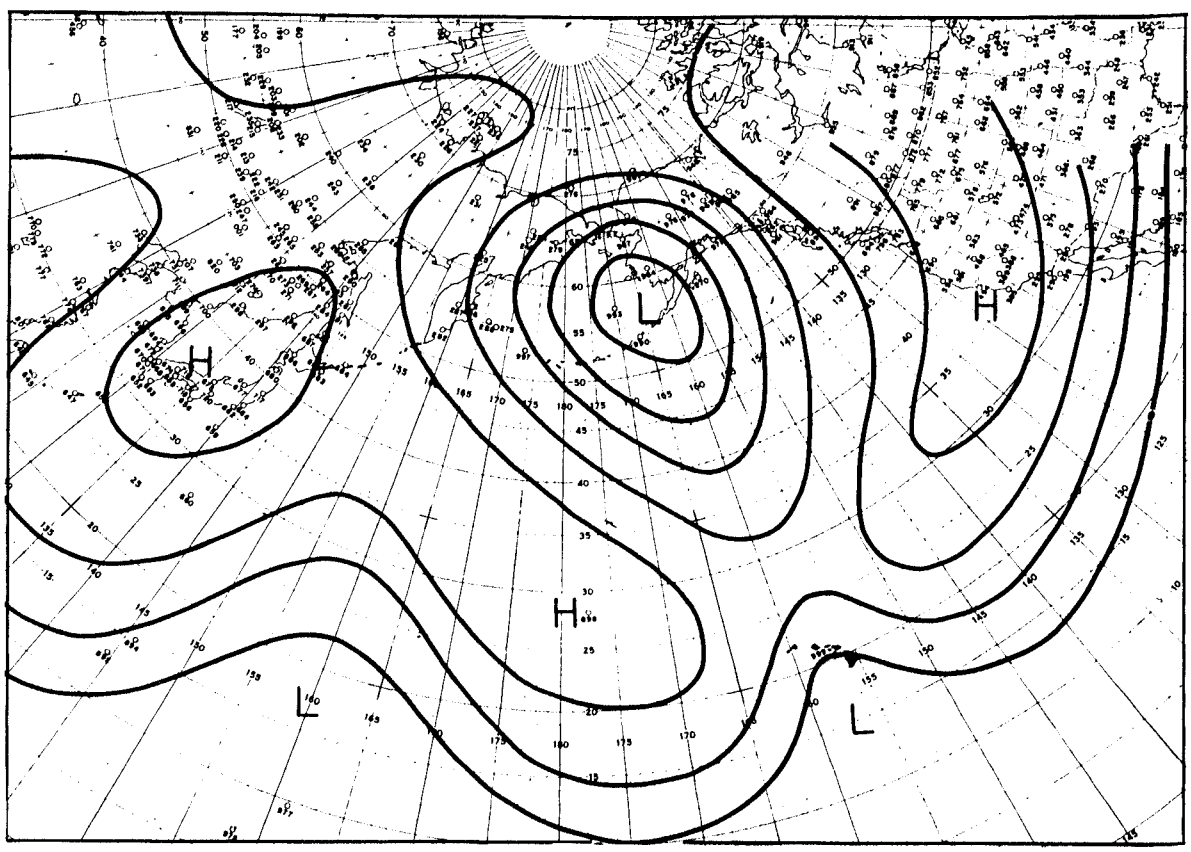


Figure 35. - Ideal pressure for general heavy rain.

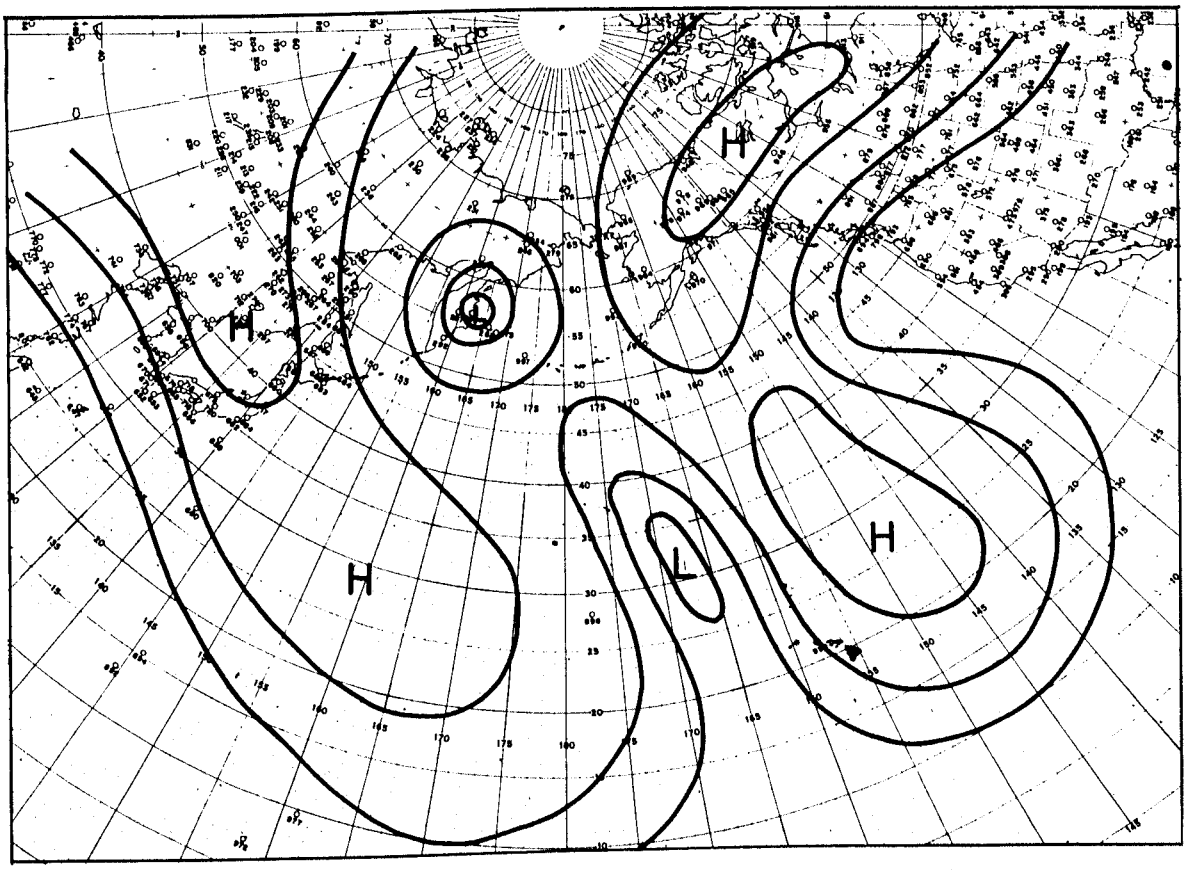


Figure 36. - Ideal pressure pattern for heavy rain on Kauai.

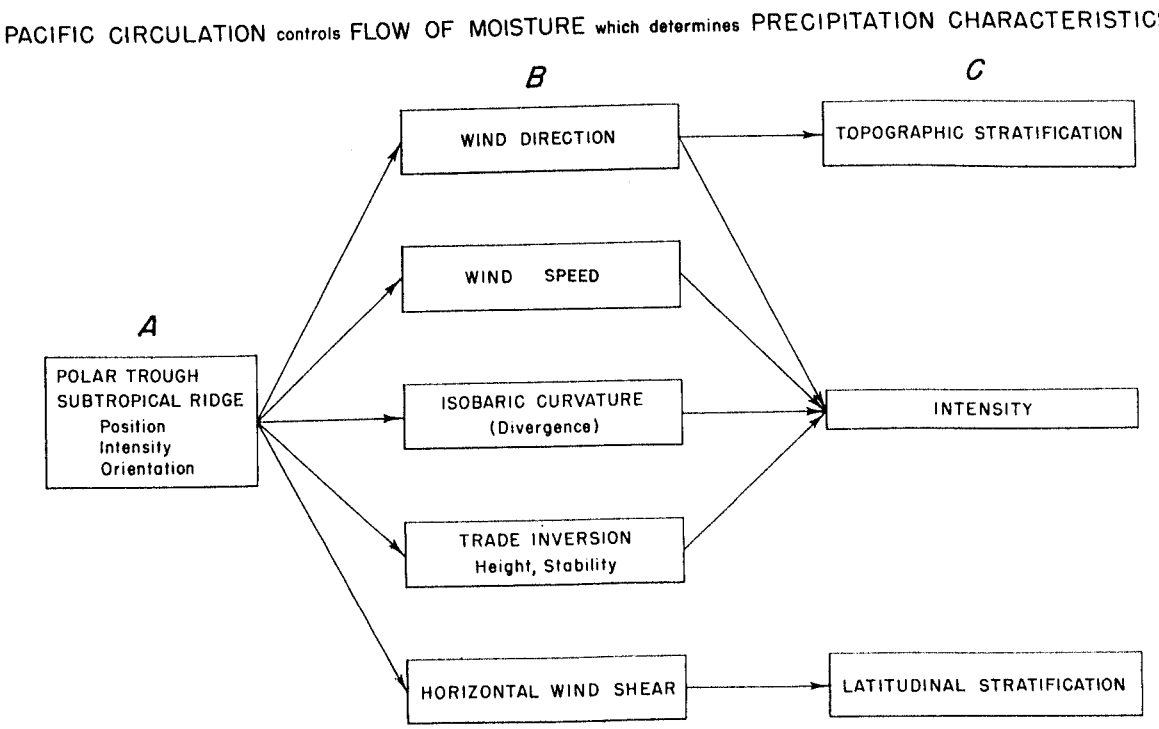


Figure 37. - Schematic representation of Pacific circulation, moisture flow, and Hawaiian precipitation characteristics.

CONCLUSION

At the outset the purpose of this work was stated in the form of two problems to be solved. An attempt is now made to provide answers to these.

The complexities of the rainfall which have been discussed in this paper can best be summarized in the form of figure 37. Fundamentally "A" comprises the available forecasting tools, "B", the parameters in the rainfall equation, and "C", the elements to be forecast. It has been shown in some detail how the various elements of "A" affect each of the "B" parameters. The wind direction determines what proportion of the horizontal flow will be converted into vertical motion, and since this varies with the surface contours in each region, it is the principal cause of stratification by aspect or topography. The wind speed determines the rate of moisture flow, and thus directly affects rainfall intensity. The convergence produced by the circulation, here described as isobaric curvature, determines another component of vertical motion. The height of the trade-wind inversion measures the available supply of moisture, and the stability governs the amount of distortion to which the inversion surface will be subjected. All of these factors are important in the rainfall intensity. Since the Islands extend over a considerable distance, it is to be expected that any marked horizontal wind shear will be reflected in a latitudinal gradient of rainfall pattern. It has been shown that the stratification by islands is to a large degree caused by latitudinal differences rather than by differences in the topography of the islands.

The orographic component is present in every type of precipitation. Thus we may broadly classify rainfall as:

1. "Pure" orographic rain
   a. trade-wind rain
   b. sea-breeze rain
   c. local convective rain
2. Cyclonic rain to which is added the orographic component
   a. rain from polar troughs
   b. rain from tropical troughs (easterly wave)
   c. rain from a combination of a and b

Heavy rain is associated with cyclonic disturbances and either a high trade-wind inversion or the absence of an inversion.

In the light of the foregoing discussion it is possible to give at least a qualified answer to the two questions concerning the indices necessary and sufficient to describe Hawaiian rainfall, and the recognition of the variations in these indices on mean circulation charts.

1. It may be definitely stated that no classification can be complete which does not include two types of station groupings:

   a. by aspect to a given wind direction or, in other words, the slope of the ground in any given direction; classification by aspect with respect to the prevailing trades (windward and leeward) is most important, but there is reason to believe that further refinement is necessary.

   b. by latitude; for this purpose grouping by islands seems sufficient.

2. Whenever the mean monthly chart presents a "pure" pattern, that is, it bears considerable resemblance to one of the ideal patterns, the pressure-anomaly pattern is amenable to interpretation in terms of rainfall. More difficulty is encountered with mixed patterns, however. It is evident that more information is needed about the way in which individual patterns combine to form the mean.

This suggests two lines of approach for further study; further definition of orographic regions, and a study of the synthesis of both circulation and rainfall patterns.

ACKNOWLEDGMENT

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