HYDROMETEOROLOGICAL REPORT NO. 39

PROBABLE MAXIMUM PRECIPITATION IN THE HAWAIIAN ISLANDS

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*No. 24. Maximum possible precipitation over the San Joaquin Basin, Calif. 1947.
*No. 25. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 1947.
*No. 25A. Representative 12-hour dewpoints in major United States storms east of the Continental Divide. 2d edition. 1949.
*No. 26. Analysis of winds over Lake Okeechobee during tropical storm of August 26–27, 1949. 1951.
*No. 27. Estimate of maximum possible precipitation, Rio Grande Basin, Fort Quitman to Zapata. 1951.
*No. 28. Generalized estimate of maximum possible precipitation over New England and New York. 1952.
*No. 29. Seasonal variation of the standard project storm for areas of 200 and 1,000 square miles east of 105th meridian. 1953.
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No. 32. Characteristics of United States hurricanes pertinent to levee design for Lake Okeechobee, Florida. 1954.
No. 33. Seasonal variation of the probable maximum precipitation east of the 105th meridian for areas from 10 to 1,000 square miles and durations of 6, 12, 24, and 48 hours. 1956.
No. 34. Meteorology of flood-producing storms in the Mississippi River Basin. 1956.
No. 35. Meteorology of hypothetical flood sequences in the Mississippi River Basin. 1959.
No. 36. Interim report on probable maximum precipitation in California. 1961.
No. 37. Meteorology of hydrologically critical storms in California. 1962.
No. 38. Meteorology of flood-producing storms in the Ohio River Basin. 1961.

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PROBABLE MAXIMUM PRECIPITATION IN THE HAWAIIAN ISLANDS

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Chapter I

PURPOSE, AUTHORIZATION AND SCOPE

Purpose of report

1.01. The purpose of this report is to present criteria for estimating probable maximum precipitation for basins in the Hawaiian Islands in connection with proposed flood-control structures.

Authorization

1.02. The authorization for this study is contained in a memorandum to the Hydrometeorological Section of the Weather Bureau, from the Office of Chief of Engineers, Department of the Army, dated November 7, 1961. This memorandum requested that "a generalized probable maximum precipitation estimate study be prepared for all the islands of Hawaii." The Corps of Engineers supported the preparation of this report by the Weather Bureau.

Scope of the report

1.03. There are no large drainage basins in the Hawaiian Islands. Probable maximum precipitation (PMP) criteria are presented covering durations up to and including 24 hours.

The topographic forms of the islands cause marked local variations in intensity of rain in storms. How much detail of the variation in the probable maximum precipitation about these topographic features is warranted, or indeed can be determined, is a formidable problem. This aspect of the report is covered in chapters II and V. Suffice it to say here that estimates in this report are based on generalized topography maps of a 1:240,000 scale.

On figure 1-1 the Hawaiian Islands are superimposed over other states on the same scale, to give perspective of the size of the region involved.

Chapter II

APPRAISAL OF THE PROBABLE MAXIMUM PRECIPITATION PROBLEM IN THE HAWAIIAN ISLANDS

Introduction

2.01. The derivation of probable maximum precipitation for the Hawaiian Islands was approached by first establishing a base non-orographic probable maximum precipitation and then adjusting the base value for the island topography (chapter V). For a discussion of general problems connected with estimation of probable maximum precipitation in an orographic region, the reader is referred to chapter II of Hydrometeorological Report No. 36 (1). Our attention here is directed primarily to aspects of the probable maximum precipitation problem peculiar to the Hawaiian Islands.

Character of island topographic forms

2.02. Long extensive barriers, such as the Sierra Nevada in California, do not exist in the Hawaiian Islands. Rather the topography is best characterized by either relatively isolated peaks (Mauna Loa and Mauna Kea on the Island of Hawaii) or ridges of small horizontal extent (the Koolau ridge on the Island of Oahu). A judgment is required on the effectiveness of such relatively isolated topographic forms in forcing the moisture-laden air to rise. Observed data (i.e., clear skies near the summit of Mauna Loa while rain falls at low elevations on the Island of Hawaii) show that the trade winds tend to flow around instead of over the higher mountains.

Dickey (2) in studying this tendency for wind to go around instead of over mountains ("corner effect") at Barter Island, Alaska, concluded that perhaps "...the complete explanation of wind anomalies...lie in the study of airflow around as well as over arbitrarily shaped barriers". As Dickey points out, stability in the lowest layers makes this effect noticeable in arctic regions. In the Hawaiian Islands the predominance of the trade inversion undoubtedly aids in the deflection of air around the islands. Judgment in regard to the prevalence and character of such an effect in the Hawaiian Islands involves both conditions during observed rainstorms and considerations of likely modifications during extreme rainfall. For example, heavy rains are common along the northeast coast of Hawaii. In the probable maximum rain in this area, optimum instability and other factors would favor more air rising over and less air being diverted around the obstacle than in an average rainstorm. This would mean greater relative orographic intensification of the rainfall due to the added lifting of the air. Thus, in the PMP case, judgment is needed in assessing what the effects of these instability and wind differences would be on both the pattern and magnitude of the probable maximum precipitation.

In a recent study of shower activity in the vicinity of the Catalina

Mountains near Tucson, Arizona, Silverman (3) concludes: "One of the most significant points revealed by this study was the preference of the airstream to flow around rather than over the mountains".

Two additional problems connected with the mountainous character of the islands need mentioning. First, there is the matter of some extremely abrupt ground slopes and of valleys with precipitous sides stemming from the volcanic origin of the islands. The character of the windflow near such obstacles in rainstorms is not known and difficult to hypothesize. In addition the matter of forced transverse convergence due to narrowing valleys needs to be confronted. Only the more important of these configurations are given consideration (par. 5.15). This problem is particularly acute on the Island of Kauai (par. 3.01). The other problem is the likelihood of there being significant island-to-island effects on rainfall capabilities. For example, the high peaks of Hawaii undoubtedly decrease the effectiveness of the rain-bearing winds to the southern slopes of east Maui.

Precipitation processes

2.03. Another problem of special importance to the Hawaiian Islands concerns precipitation processes. On most rain days on the islands the clouds remain below the freezing level so that the Bergeron-Findeisen ice-crystal process is not operative. However, for the more intense rains, as in the probable maximum rainstorm, the extended vertical development of the clouds would make it likely for the ice-crystal process to come into play. Both the degree of vertical cloud development and the precipitation process operating in the Hawaiian Islands work to create a greater disparity between rainfall distribution patterns in the probable maximum precipitation case as compared to the average rain day. This means that index maps such as the mean or median annual rainfall maps are of considerably less use in PMP procedures in the Hawaiian Islands, than, for example, in California (1).

Anomalous winds associated with extreme rains

2.04. Wind problems exist in connection with PMP estimates in Hawaii in addition to the "corner effect" covered in section 2.02. The chief problem centers around the fact that on days with really excessive rains the winds may differ considerably in direction (and speed) from those prevailing on days when the rainfall is not extreme. Therefore, again the mean annual and similar charts are not valid index patterns for the PMP. Section C of chapter IV is devoted to this wind problem.

Moisture distribution and variation

2.05. In addition to the influence of the trade inversion on the vertical moisture distribution (figure 3-3), the relatively small seasonal variation in moisture in the mean (figure A-1) and particularly in the extreme (figure A-2) introduces a problem regarding seasonal variation of the probable maximum precipitation. The resolution of this problem is covered in part in chapter IV, (i.e., par. 4.11), leading to the conclusions presented in section F of chapter V. Suffice it to say here that despite the somewhat higher moisture potential in summer, the greater efficiency of rainfall mechanism in the cooler season (i.e., the October through April period of lessened trade wind control) causes the cooler-season larger-area thunderstorm to produce higher precipitation values for areas and durations of interest.

Influence of geographical location

2.06. The location of the Hawaiian Islands (figure 2-1) involves factors which may possibly have some bearing on the general level of the PMP. One of these factors is the pronounced influence of the rain-inhibiting trade inversion. The marine setting in which the islands are found is one classified as near-desert in regard to annual rainfall. This suggests that perhaps the capabilities for rainfall for durations as long as 24 hours may be somewhat less than areas located farther from the subtropical high pressure areas. The thought here is that, even though the trades (and inversion) may be completely disrupted or displaced for a period, nevertheless the displacing synoptic system is likely to draw into its circulation some of the ambient drier air, particularly when durations of as long as 24 hours are considered.

Conclusions

2.07. The several problems enumerated above lend emphasis to the important role of judgment in providing probable maximum precipitation estimates for the Hawaiian Islands. The existence of numerous difficult judgment factors (in addition to those present in probable maximum precipitation estimates for some other area), in turn, indicates that a simplified presentation is the most logical. The simplified presentation includes a single geographical distribution of rainfall for the various durations of the PMP. To attempt variation, considering the lack of definitive solutions to some of the problems enumerated above, would be presumptuous for island forms of the character presented by the Hawaiian Islands. (See also par. 6.01.)

In spite of some noteworthy progress in theory in the last decade in dealing with complex orographic regions like the Hawaiian Islands, the conclusion of Fletcher (4) in 1951 still basically applies. At that time, in reference to topographically complex regions Fletcher stated,

> "Present deficiency in theoretical knowledge of the effects of topography upon the space distribution of wind leads to the conclusion that an empirical approach must serve for many problems involving orographic rainfall until adequate theory is developed".

Chapter III

GENERAL CLIMATOLOGY OF THE HAWAIIAN ISLANDS

Climatic controls

3.01. In addition to the marine influence, the climate of the Hawaiian Islands, particularly in regard to the rainfall regimes, is controlled by three factors. First, is the predominance of the trade regime. Figures 3-1 and 3-2 (5) show the importance of the northeast trades in terms of Hawaii's position relative to the Pacific subtropical High. The critical character of the island location (that is, whether under the influence of the trade winds or middle latitude westerlies) is obvious from the wind histograms plotted on figure 3-2. The sharp curtailment of the trade control is evident as one passes to the north of the islands. From close to 100 percent domination in midsummer the trade predominance decreases to near 50 percent in midwinter. Figure 3-3 shows the effects of the predominant trades in the form of the variation in the degree of saturation with elevation. Even for a wet winter month, (December 1954) when Hilo received 50.82 inches of rain, the drying effects of the trade inversion are still in evidence in the mean monthly upper air sounding. The marine influence shows up in this figure in terms of the high percentage of moisture in the low levels.

The second important controlling climatic factor is the pronounced orographic character of the islands stemming from their volcanic origin. Considering all of the islands, about 50 percent of the land is above 2000 feet while maximum elevations on the major islands range from 3370 feet on Lanai to 13,784 feet on the Island of Hawaii (6). Considering relatively small scale slopes, the Island of Kauai has slopes of 0.20 or greater on about 50 percent of its area while the Island of Hawaii has less than 5 percent of its area with slopes of 0.20 or greater (7).

The relatively infrequent but important cyclonic disturbances represent the third major climate control. These storms vary in type and intensity but they have in common the characteristic of disrupting to varying degrees the dominant trade circulation and prevailing wind regime of the islands. The discussion of these important cyclonic disturbances is covered in chapter IV.

Wind as a factor in the general climatology

3.02. From a general climate viewpoint the trade winds are the dominant influence; primarily in summer when they are, on the average, strongest and most persistent. However, some sheltered areas of the islands - such as parts of the western coast of Hawaii - never, or hardly ever, experience the trades. This is due to the distortions brought about by the more important topographic forms which permit local land and sea breezes to be the dominant circulation in these sheltered areas. The deep narrow canyons and precipitous slopes also contribute to complicated local, but more infrequent, wind regimes. In general, the trades dominate the windward areas, while in the sheltered leeward areas (and in some windward areas such as around Hilo) local wind regimes predominate. It is a matter of much significance that the strongest winds of consequence (for PMP estimates) are most likely in the cooler season in connection with storms of a cyclonic character. The synoptic climatology of these heavy rain-bearing winds is covered in chapter IV.

Annual rainfall regimes

3.03. It is estimated (6) that the average annual over-ocean rainfall in the vicinity of the Hawaiian Islands is a scant 25 inches. The presence of the varied topographic forms results in intensification to the extreme extent, on one hand, of boosting the average annual rainfall to over 460 inches on Mount Waialeale, Kauai and, at the other extreme, of depleting the rainfall by sheltering so that Kawaihae, Hawaii receives on the average only 6.5 inches a year (7). The relative persistence of the trades, in tending to fix the areas of orographic intensification and sheltering, accounts for the extreme variations in observed median annual rainfall. A few important cyclonic storms in a given season, on the other hand, can do much to eliminate these vast differences mainly due to their function of bringing heavy rains to the normally sheltered areas. Thus, for a particular season the departures from the mean may be extremely large in Hawaii and are mainly a function of the degree of control by cyclonic disturbances compared to the trades. Recent evidence (8) shows that wet trades are also distinguished by the existence of at least minor cyclonic disturbances aloft.

Figures 3-4 through 3-8 show the median annual precipitation (9) for the islands. Precipitation regimes (mean monthly precipitation) for selected stations on each island are shown on figures 3-9 through 3-13. Maximum monthly and daily precipitation amounts are also shown for comparative purposes. The range of annual precipitation on the Island of Hawaii is typical of the islands in general except Lanai where the maximum is less than 40 inches. The interception of the persisting trades is clearly evidenced by the large windward median annual precipitation values. The importance of the control exerted by the dry air above the trades in combination with the diversion of the air around the island also is clearly shown by the small median annual rainfall values (less than 20 inches) in the vicinity of and to the lee of the peaks. The centers of rainfall along the western portion of the island result from a combination of relatively steep slopes which interact quite frequently with the primarily local land-sea breeze regime (mainly in the warm season) and infrequently with the more important major cyclonic storms (in the cool season).

While the above discussion of the rainfall on the Island of Hawaii points up significant differences that exist on an island, it must be remembered that each island has its own individual rainfall characteristics. East Maui (figure 3-5) has mountains extending above the trades like Hawaii and similarly has its maximum annual precipitation centered at 2- to 3-thousand feet elevation on the windward side. The lower mountains of west

Maui show maximum annual precipitation at higher elevations. This is undoubtedly due to the frequent lifting of trade air across, rather than largely around, these mountains. Oahu (figure 3-7) with its low ridges of 2- to 3-thousand feet shows its maximum just leeward of the ridge line due to a slight carry-over of precipitation initiated on the windward slopes. The narrowness of the ridge is a favorable factor for such a distribution (10).

Seasonal variation of monthly rainfall

3.04. The similarity of patterns of median monthly precipitation to the median annual is striking for the islands in general. Nevertheless there are rather distinct seasonal characteristics resulting from the interaction of the three primary controls mentioned at the beginning of this chapter.

Seasonal variation of extreme precipitation is covered in chapter V. In chapter III the main concern is with seasonal variation of rainfall from the point of view of the prevailing climate. Where the trades predominate the following general conclusions may be made:

(1) Winter is the season of highest precipitation for the lowest 2- to 3-thousand feet. In general the difference between winter and summer precipitation becomes less when the annual precipitation is great.

(2) For intermediate elevations (i.e., 3- to 5-thousand feet), particularly at the rainier locations, summer rainfall totals may equal or even exceed winter totals. One possible explanation of this may be that the potential for periods of heavy rains is present in summer but because of the more pronounced trade inversion the equivalent of several thousand feet lift is often needed before the convective instability (and therefore significant rain) can be realized. Thus, the intermediate elevations are in the most favored situation to realize this rainfall, particularly because of the rarity of cyclonic disturbances capable of producing sufficient convergence-produced low-level lift.

(3) At the higher elevations (only Hawaii and Maui have significant areas above 5000 feet) winter rainfall generally predominates.

For areas sheltered from the trades, which usually are areas of low rainfall such as the kona region of Hawaii, summer rainfall predominates. Frequency of occurrence and greater effectiveness of the land-sea breeze regime probably over-compensate for the relatively infrequent major cool-season storms.

The above discussion covers only some of the major features of the seasonal variation of precipitation as can be seen by reference to monthly precipitation values on figures 3-9 through 3-13. Actually at many stations the seasonal rainfall distributions are bimodal or trimodal.

Rainfall variability

3.05. For all areas of the Hawaiian Islands and for all durations of rainfall large variability from season to season is characteristic. The monthly March precipitation at Honolulu is shown in figure 3-14 as typifying the large variability characteristic of the island rainfall. Of more concern to estimating maximum precipitation for the Hawaiian Islands is the all-time record Honolulu 24-hour rainfall (17.41 inches, March 5-6, 1958). The significance of such a storm is discussed in chapter IV.

Rainfall intensity

3.06. Relatively intense rains have been reported from all parts of the Hawaiian Islands although favorably located regions receive such rains much more frequently. "Climate of the States" for Hawaii (6) sums up the situation by stating, "In general all stations in Hawaii for which there are as much as 50 years of record have experienced daily rains of at least 8 inches, and the majority have experienced falls of 12 inches or more". Figure 3-15 shows the location (with data) for the ten greatest daily rainfall amounts for the islands. Most of these are in the 20- to 30-inch range. As can be seen all the major islands have shared in the highest ten cases. However, Hawaii and Kauai have each had four occurrences out of the ten highest.

Chapter IV

SYNOPTIC CLIMATOLOGY OF MAJOR HAWAIIAN STORMS

4.01. Chapter III presented a birds-eye view of the general trade-dominated climate of the Hawaiian Islands with emphasis on the rainfall-related aspects of the climate. The purpose of chapter IV is to deal with the less frequent but more important (for PMP considerations) non- or disrupted-trade conditions. The disruption of the trade regime may be localized and result in important small-scale rains only or may be a general breakdown and result in relatively large-scale rainstorms affecting all islands. In order to estimate probable maximum precipitation for the Hawaiian Islands the type of storm most likely to yield extreme rains needs to be established. In addition to this, chapter IV deals also with the role of thunderstorms in significant Hawaiian rains, with the synoptic climatology of rain-bearing winds and with the hurricane threat.

A. PROTOTYPE OF HAWAIIAN PMP STORM

Introduction

4.02. Nearly all basins in the Hawaiian Islands are less than 50 square miles in area (11) and only a few exceed 15 square miles. Storms, therefore, which are controlling for areas of up to 50 square miles become important for probable maximum precipitation in the Hawaiian Islands. Since some of the highest observed Hawaiian precipitation amounts occurred in storms of recent years, a study of these storms is instructive for probable maximum precipitation determination. Hypotheses and interpretation of observed phenomena are enumerated, followed by a discussion, the purpose of which is to establish the Hawaiian PMP storm type.

Hypotheses

1. There are various types of disturbances or disruptions of the trades conducive to Hawaiian precipitation.

2. The March 5-7, 1958 storm on Oahu and the January 24-25, 1956 storm on Kauai fit the description of effective disturbance and exhibit synoptic features which make either (or a synthesis of the two) a prototype of the Hawaiian probable maximum precipitation storm.

3. An approximately stationary or slowly moving narrow zone of strong convergence, unrelated or only remotely related to topography, is the primary rain-producing feature of the probable maximum precipitation storm for the Hawaiian Islands. The added feature of a quasi-stationary (or cold) front as in the January 1956 storm contributes to the more intense short duration rainfall.

4. There exists world-wide, for regions subject to continued invasion by warm moist air masses a "Thunderstorm-Infested Fixed-Convergence Area" type of weather situation in which a general level of convergence-produced rain is permeated with heavier bursts. The thunderstorm is an important part of this type as an indication of intense upward vertical motion and possibly in other ways as yet incompletely known, but does not account for all, or even most, of the heavy rain.

5. For durations measured in hours and areas other than the smallest the "Thunderstorm-Infested Fixed-Convergence Area" (hereafter referred to as the TIFCA type) will control the probable maximum precipitation in the Hawaiian Islands. For durations measured in minutes and over very small areas, the isolated convective thunderstorm type may control.

6. Continued moist inflow is a prerequisite of the TIFCA type if it is to be effective for durations of more than an hour or two.

7. Local orographic differences in Hawaiian rainfall decrease with increasing rainfall intensity; in the probable maximum precipitation storm, differences due only to relatively steep slopes and to depletion of moisture by high mountains will be effective.

Synoptic study of recent Hawaiian storms

4.03. Recent Hawaiian storms embrace many record-breaking rains and offer some perspective of significant synoptic features. Among the storms considered were the following:

1. November 27-30, 1954
2. November 8-12, 1955
3. December 19-23, 1955
4. January 24-26, 1956
5. March 5-7, 1958
6. November 1-3, 1959

The prominent features of these significant rain periods were: (a) the presence of thunderstorms (considered generally to be a relatively infrequent phenomenon in the Hawaiian Islands), (b) the presence of some disturbance of the prevailing trade regime.

Due to the inhibiting effect of the trade inversion on the vertical development of clouds, moderate showers are generally the most that are produced in the essentially undisturbed trades, with the tops of the trade cumuli limited to 7-8 thousand feet. However, on occasion some rather substantial showers may occur under these conditions. The degree of vertical development in other cases will depend upon how thoroughly the trade inversion is displaced, coupled with the inherent instability (in depth) of the moist air. In the words of Weather Bureau forecasters at Honolulu (12) "the suppressing effect of the inversion must be overcome before rainfall may become heavy and general in the islands."

Various types of disturbances were present in the storms surveyed. Since these were all significant rainstorms, it is not surprising that four out of the six storms studied had a definite cyclonic circulation either at the surface or aloft (i.e., 500 mb or above) or both. Consideration of the rain periods in the six storms studied and others indicated that a disturbance of the trades may range from simply a freshening of the trades themselves, resulting in sufficiently concentrated low level convergence and increased activity, to a severe kona in which the trades are temporarily but substantially eliminated.

The commonly accepted meaning of the word kona is a situation with surface winds from the leeward side of the islands which brings rain to these areas (leeward in reference to the prevailing trades). Simpson (13) defines the kona cyclone as "essentially a cold-core low, of large size and dominant importance to circulations in the middle and upper troposphere, where it is usually secluded from the main stream of polar westerlies." In discussing the kona cyclone Simpson concludes, "Once formed... the kona cyclone seems to have the same general structure and behavior, regardless of the source from which it evolves." Usually it is agreed that in kona situations cyclonic circulations exist both at the surface and aloft, although in some cases the Low at the surface does not show up until late in the period.

Numerous other synoptic features and combinations thereof may provide the necessary mechanism for partial or complete elimination of the trade inversion with accompanying abnormal vertical cloud development and significant precipitation. Among these synoptic features are quasi-stationary or moving surface troughs, shear lines or fronts, easterly or westerly moving troughs aloft, tropical storms (decaying or otherwise), or lastly, just a weak trade situation that allows for increased local convective activity with some interaction with sea breezes. Riehl (14) covers a number of these disturbances of the trades in his discussion of Hawaiian rainfall.

The instability in the major Hawaiian rainstorms was investigated by use of the Showalter Stability Index (also par. 5.19). This stability index provides an estimation of the degree of bouyancy (or tendency to overturning) of the air. It is computed by first lifting the 850-mb air dry adiabatically to saturation and then moist adiabatically to 500 mb. The resulting 500-mb computed temperature is then subtracted algebraically from the actual 500-mb temperature. Large positive values indicate stability (i.e. the lifted air is colder than its surroundings). The results showed values close to zero to be common near the time of significant rainfall, with values occasionally dropping to -2 or -3 for short periods in some storms. In the Mississippi Report (15), it is pointed out that significant rains are associated with instability values of +1 or less. Siler (8) found the Showalter index was generally below +2 in heavy Hawaiian rain cases although some notable exceptions were found.

March 1958 storm as PMP type

4.04. The March 1958 storm can be classified as a kona-type disturbance in which a closed cyclonic circulation existed to high levels. Figure 4-1 compares some features of the March 1958 storm with mean surface kona conditions as presented by Simpson (13). In this storm a relatively fixed zone of convergence provided the necessary means of rapid processing of the moist lower layers and the resulting vertical motion favorable for excessive buildups of the cumulus clouds. A 24-hour downpour accompanied by occasional thunder and lightning was the result. An aircraft in flight reported an extensive area of cumulonimbus buildups eastward from Honolulu. Blumenstock (16) describes this heavy rain as having fallen "along a narrow zone of convergence that was squarely centered over Oahu and kept feeding into this zone from the south."

The departure-from-normal 700-mb chart (17) for the period March 4-8, 1958 showed a departure of -290 feet northwest of the Hawaiian Islands. Contrasted to this were large positive departures amounting to 640 feet in the High south of the Aleutians. This supports the contention that the anomalies of the large-scale features are important in significant disruptions of the trades. A semi-schematic diagram adapted from figure 7 of Green's article is shown in figure 4-2.

During the 24-hour period from 3 a.m. on March 5 to 3 a.m. March 6, the downtown office of the Honolulu Weather Bureau received 17.41 inches while the airport station had almost as much, with a total of 17.07 inches. The 17.41 inches at the city office eclipsed by nearly four inches their previous record 24-hour fall (13.52 inches on March 19-20, 1917). The hourly rainfall for Honolulu is shown on figure 6-7. Figure 3-14 shows strikingly how this unusual 24-hour rainfall compares to monthly March rains at Honolulu.

During the March 1958 storm all stations on Oahu reported 2-day totals of at least five inches. Figure 6-3 shows the analysis of the March 5-6, 1958 rainfall based on stations reporting precipitation in the morning. The highest officially published amount (Climatological Data) was 24.1 inches at Lunalino Home situated in southeastern Oahu in a valley just west of Koko Crater. However, there were unofficial reports of up to 26 inches. In the 3-day period March 5-7, 1958 the rainfall totals amounted to 50 to 80 percent of the total median annual precipitation along the leeward southern coastal areas of Oahu.

In a kona storm like that of March 1958 the orographic effects are diminished because a more nearly uniform level of precipitation is produced from a non-orographic convergence mechanism. This relatively uniform level of precipitation is evident from figure 4-3 where a nearly 1800-foot difference in elevation does not appear to have any noticeable effect on the magnitude of the rain. Riehl (14) in earlier work on Hawaiian Rainfall emphasized that, "The larger the rainfall the greater becomes the relative homogeneity of storms. As storm intensity increases, the importance of the orography declines."

Support for concept of PMP synoptic situation

4.05. It is significant that the same basic rain-favoring features displayed by the March 1958 storm resemble markedly features of record

24-hour rains in other parts of the world. Weather Bureau Technical Paper No. 33 (18) refers to the flood-producing rains in the South Central United States in April, May and June 1957 as being caused by "forced ascent of tropical air in convergence zones in the vicinity of quasi-stationary frontal surfaces" and also "much of the precipitation in the flood area fell as heavy showers during severe thunderstorms."

The TIFCA type that is of concern here can be associated with a continuing succession of thunderstorms over a fixed zone as moist air flows (sometimes at quite strong velocities) into and out of the intense rain area (19). Thus more or less continuous rain can occur for 24 hours or more with several peaks of greater intensity. The description of a relatively fixed rain area in the July 1951 Kansas storm (19) is typical, with the "front remained nearly stationary over the area for several days" in spite of a "very strong northward flow of warm, moist air into the heavy rain area." The typical situation for occurrence of record-breaking rains calls for upward vertical motion of varying intensity persisting over thousands of square miles, with more intense upward vertical motion in a more restricted area of thunderstorms within the larger area.

The significant thunderstorm-rain situation in the tropical Congo Basin seems to exhibit similar features as described by Trewartha (20).

> "As a rule there is a tendency for these instability storms to be concentrated in greatest numbers in close proximity to the boundary marking the convergence between easterly and westerly circulations, and more especially where the convergence is strongest--Here the thunderstorms may be so numerous that they are in the nature of organized systems." (Underlining ours.)

Some recent radar studies tend to further support the envisioned prototype as one which is, in general, applicable to extreme rain occurrences. The following are cited in this connection:

(1) From radar studies of heavy rains in Illinois, F. A. Huff (21) reported at the Eighth Weather Radar Conference, "Thus, storms producing heavy rain intensities appear to be considerably larger than the average convective system." Huff also pointed out, in connection with the longer duration storms giving 10 inches or more of rain, that "all occurred with quasi-stationary squall zones through which several lines or groups of thunderstorms passed."

(2) Ralph J. Donaldson (22) had this to say concerning reflectivity in New England thunderstorms,

> "Evaporation would be a minimal effect in a mature storm core, which would be shielded from the invasion of dry environmental air by its location within the protective boundary of several miles of moderate rain in some directions and at least a sheath of heavy rain all around."

(3) Pauline Austin (23) in studying New England squall lines noted results confirming the fact "that intense storms occur in groups which may often persist for several hours although the individual convective cells have much shorter lives." The envisioned prototype would occur when the convergence area resulting in these groups of thunderstorms remains fixed over a region.

The above situations appear to have been quite similar to the prevailing conditions in the March 1958 storm on Oahu and the January 1956 storm on Kauai. The primary feature which these various situations have in common is an area of convergence which is considerably larger than individual thunderstorms so that intense thunderstorm rainfall is superimposed on a larger area of background rainfall. Such a picture of the probable maximum precipitation situation consisting of a pronounced convergence area with imbedded thunderstorms is to be distinguished from the isolated convective (smaller scale) thunderstorm situation. The isolated thunderstorm situation, usually associated with weak gradient conditions, etc., although capable of small area intensive short duration rainfall, is not usually a situation conducive to really maximum precipitation, particularly for durations measured in hours.

Others who have worked with Hawaiian rainfall data have recognized that it is other than the isolated thunderstorm situation that is important in heavy rain situations. In an earlier study Leopold (24) pointed out that Hawaiian "rainfall usually comes from large but discrete cloud masses mostly of the cumuli-form type. A rainy day is characterized by increased size and number of cumuli-form clouds." More recently the group of Hawaiian forecasters mentioned earlier (12) come even closer to describing the Hawaiian heavy rain-producing situation with the words, "... convergence... through a relatively deep layer... continuous light rain for long periods... occasional bursts of heavier rain from cumulonimbus that infest the circulation." Extending this situation to the probable maximum precipitation case results in an increase in the intensity of the level of the background rain to more than just light. Parry (25) sums up the situation which is conducive to really heavy rain in Hawaii with the words, "a stationary convergence pattern with an intake of air from the south... continuing long enough to produce major amounts of rain."

Some weather satellite photographs in recent years are suggestive of another important feature (as distinguished from isolated thunderstorm activity) of the envisioned PMP prototype. The very bright weather satellite cloud areas such as displayed (i.e., area B) in the May 16, 1960 synoptic situation (26) likely result from a relatively large area of organized convergence infested (or capable of being infested) with thunderstorm activity. The bright cloud area mentioned was surrounded by an especially darkened area. This is strongly suggestive that the bulk of the compensating downward motion occurred well removed from the relatively large area of organized convection. Such a feature (i.e., little close-in, downward motion) may indeed be a vital part of the situation truly conducive to giving probable maximum precipitation for durations up to around 24 hours. Thus, with the bulk of the downward motion occurring well removed from the primary area of heavier rainfall (which, in the envisioned prototype remains relatively fixed), the rain-inhibiting factor due to entrainment of drier air is not a problem. The smaller area of more intense activity can perhaps be thought of as a "protected core" within a relatively large area of significant convergence, just as an interior cell of a single large thunderstorm of many cells can be considered a "protected core" (27) essentially unaffected by the drier environmental air.

Conclusions

4.06. The March 1958 storm on the Island of Oahu is considered as having most of the essential features conducive to the probable maximum precipitation storm for the Hawaiian Islands. The primary feature which makes it the PMP type is a relatively fixed zone of convergence conducive to general upward vertical motion with regenerative smaller areas of more intense vertical motion embedded in the larger convergence area. Such a situation requires a rather significant sustained inflow of moist air. A continuing rich supply of moisture combined with a minimum of dry air entrainment set the stage for the PMP storm. Since the involvement of a quasi-stationary (or cold) front appears often significant in the more intense short duration portion of the rainfall, this feature (such as in the January 1956 storm of Kauai) is also a desirable part of the envisioned PMP type. For durations measured in minutes over very small areas, the isolated convective thunderstorm may be the dominant type by virtue of its greater capability of maintaining a vertical shaft of precipitation. However, the same lack of winds which makes this possible, also results in a built-in limitation on duration by virtue of a lack of sustained inflow of moisture from outside the immediate environs as well as the mechanism for prolonged convergence over a fixed area.

The TIFCA concept was introduced as descriptive of the envisioned synoptic picture that is conducive to the production of the probable maximum precipitation. Although various synoptic configurations may bring it about, including perhaps a slow-moving or stalled tropical disturbance, it is felt that the cooler season, strong kona storm with a deep layer of convergence associated with closed circulations to high levels, is the most likely producer of the probable maximum precipitation for the Hawaiian Islands.

B. THE THUNDERSTORM AS A FACTOR IN HAWAIIAN PROBABLE MAXIMUM PRECIPITATION

Introduction

4.07. For purposes of estimating extreme precipitation for the Hawaiian Islands, it is necessary to know the role played by thunderstorms. Not that thunderstorms, per se, are necessarily important but the occurrence and severity of thunderstorms during the more important rains are indicative of characteristics of stability conditions and degree of vertical development and therefore tell something of the degree of similarity of Hawaiian extreme rainfall phenomena to that of other parts of the world.

Low elevation Hawaiian stations are comparable to California low level stations in terms of mean annual thunderstorm days. Thus, climatologically, thunderstorms are considered an infrequent event for such low elevation Hawaiian stations - understandably so when one considers the prominent role played by the trade inversion in inhibiting the vertical development of trade cumuli. However, a joint review of Hawaiian rainfall and thunderstorm statistics serves to demonstrate the importance of this relatively infrequent phenomenon in instances of heavy rainfall.

Data

4.08. Thunderstorm and rainfall data primarily from three stations (see figure 2-1) were used in this study - Hilo (elevation 31 feet) on the Island of Hawaii, Honolulu (elevation 7 feet) on the Island of Oahu and Lihue (elevation 115 feet) on the Island of Kauai. For some comparative purposes these data were restricted to the years of simultaneous recorder rainfall data at these stations - 1953 through 1960. In other instances the full but non-simultaneous airport records for these stations were used. In addition one phase of this study involved a consideration of all Hawaiian stations reporting rainfall in Climatological Data for Hawaii (28).

Rain vs. thunderstorm relations

4.09. A survey was made for occurrences of rainfall of at least 2 inches in 24 hours. The ratio of frequency of rains of this caliber for Hilo, Lihue and Honolulu is about 5 to 3 to 2 compared to a similar ratio of median annual precipitation of these stations of about 12 to 5 to 2. Days with thunderstorms as indicated in the local climatological data for these stations were noted with a result that 59 percent of the days with 2 inches or more of rain at Honolulu had thunderstorm activity while at Lihue the tally was 40 percent and Hilo 19 percent. A thunderstorm occurrence was counted when the station with the rain listed either thunder or lightning on the day of the rainfall. In spite of the relatively lower percentage at Hilo a further breakdown of the data showed the three highest 24-hour rain amounts at Hilo were all associated with thunderstorms as were the two highest at Honolulu and the four highest at Lihue. Considering the stations jointly all cases of rainfall amounts of at least 10 inches in 24 hours were associated with thunderstorms (pars. 4.11 and 4.15).

A second comparison of rainfall with thunderstorm occurrence was made using a short-duration rain threshold of one inch per hour. A combined total of 92 cases had associated thunderstorms 67 percent of the time with the following station breakdown:

Station	Cases	Percent with thunderstorms
Hilo	32	50%
Honolulu	32	87-1/2%
Lihue	28	64%

Seven of the 92 cases involved amounts of two inches per hour or greater and five of these were associated with thunderstorms. The remaining two cases were two consecutive hours on July 30, 1954 at Lihue.

A third type of comparison of thunderstorm occurrence with rainfall involved days when rain of 12 inches or more was observed. For this all published station values on all islands (Climatological Data for the Hawaiian Islands) (28) for the full period of record beginning in 1906 were considered. A total of nearly 400 instances of 12 inches or more per day resulted from this survey. In some of these, two or more occurrences were single cases since one station would report its 12-inch or greater amount one day earlier or later than another station on that island. If reported 12-inch or greater amounts were separated by as much as two days, then these were considered separate cases. The total number of separate cases was determined to be 156, extending from 1907 through 1959. Thunderstorm occurrences were considered on the basis of the storm dates plus or minus one day. Association with rainfall was done on an island-wide basis. That is, the occurrence of a thunderstorm anywhere on the island of rainfall occurrence was considered indicative of a causal relationship. Thunderstorm occurrences were based on the reports of thunderstorms as given in the miscellaneous portion section of the Climatological Data (28). The use of thunderstorm reports on an island-wide basis is considered fairly reasonable since the smallness of individual islands (except perhaps Hawaii) means a single thunderstorm report is rather indicative of the characteristics of the air mass responsible for the rain. The use of plus or minus a day is an expediency to take care of not knowing the exact time (i.e., day) of occurrence of most of the reported daily rain amounts.

Table 4-1 shows the breakdown on these cases by islands with the accompanying percentage of these cases associated with thunderstorms.

Table 4-1

DAILY RAINFALLS OF 12 INCHES OR MORE AND THUNDERSTORM OCCURRENCE

Island	Number of cases	Percentage with thunderstorms
Hawaii	71	64
Maui	37	41
Kauai	22	55
Oahu	26	69

Seasonal variation of thunderstorms

4.10. An additional analysis was made of thunderstorm days at Hilo (1952-1960), Honolulu (1949-1960) and Lihue (1951-1960). Histograms of these data plotted by year of occurrence and month of occurrence are shown in figure 4-4. For the periods surveyed, Hilo and Honolulu show a mean annual number of thunderstorm days of slightly over five while Lihue shows slightly over seven a year. Thunderstorms are conspicuous by their almost total absence at Hilo in January. No attempt is made to explain this and perhaps no explanation is called for since five occurrences of distant lightning were noted during this period. The stabilizing features of the trade inversion show up in the form of only one thunderstorm occurrence in summer (i.e., June, July and August), during the period surveyed. This single occurrence was at Lihue on August 5, 1954.

Cool season control of intense rainfall

4.11. Figures 4-5 and 4-6 are presented to demonstrate two things:

(1) Thunderstorm control of large precipitation amounts in Hawaii.

(2) Preference for cool-season occurrence of large precipitation amounts.

The second of these points is discussed with additional figures in chapter V (par. 5.18). Suffice it to say here that figure 4-6 demonstrates this for the categories of rainfall covered.

The importance of thunderstorm control is evident when one compares data for Lihue and Hilo arranged in categories of increasing rainfall as follows: (taken from data shown on figures 4-5 and 4-6).

	Number of cases	
Category	Hilo	Lihue
2"/day	72	30
1"/hour	39	31
0.50"/10 min.	14	23

This increasing frequency of shorter duration heavy rains at Lihue is a logical expectation when the increased frequency of thunderstorms at Lihue is considered. The data for 10 minutes duration is somewhat biased by a one-year longer record at Lihue but this does not significantly affect the basic deduction.

Conclusions

4.12. It is possible in the Hawaiian Islands to receive quite intense showers (i.e., cloud buildups to high levels) with either no thunder and lightning or perhaps just a moderate amount of cloud-to-cloud lightning. The demonstrated increase in reported thunderstorms above, as more intense rains are considered, serves to highlight the importance of a more thorough disruption or elimination of the trade inversion with significant vertical development of the clouds.

That the thunderstorm is to be considered an intimate part of the rainstorm which approaches PMP caliber is demonstrated by the unprecedented storm along the Hamakua coast of Hawaii on April 2-3, 1961 (see reference 35). To quote Arno,

> "On Sunday evening the intense portion of the storm started with brilliant lightning flashes, thunder, and hard down-pounding rainfall. Lightning flash vision allowed for seeing ankle-deep water running across grass-covered lawns..."

Thus, significant thunderstorm activity is a manifestation of PMP caliber rains (for durations to 24 hours) in the Hawaiian Islands as it is in regions of vastly different climates.

The conclusion drawn from the considerations above is that, although as a general climatic feature the thunderstorm is relatively unimportant in Hawaii, for really significant rains the thunderstorm takes on great importance. The thunderstorm, therefore, is rightfully considered an intimate part of the Hawaiian PMP storm type.

C. THE SYNOPTIC CLIMATOLOGY OF SIGNIFICANT RAIN-BEARING WINDS IN THE HAWAIIAN ISLANDS

Introduction

4.13. Paragraph 3.02 of chapter III dealt with the importance of the trades as a general climatic feature of the Hawaiian Islands. In this section the concern is with the anomalous and more important winds. It is necessary to set the limit on wind direction for PMP conditions in order to evaluate the effectiveness of slopes. This section concerns prevailing wind direction and speed during significant rain situations at Honolulu, Hilo and Lihue. The duration of primary concern is for 24 hours since smoothing procedures can indirectly allow for control of the shorter duration rain by winds from other directions.

Since the envisioned prototype includes thunderstorms it is instructive to also look into the occurrence of thunderstorms in Hawaii in connection with concomitant wind velocities. A few brief highlights concerning thunderstorm-wind relations from recent literature is instructive in this connection.

Evolution of concepts of thunderstorm - prevailing wind relations

4.14. Up until quite recently it has been customary to think of thunderstorm development (i.e., growth of relatively vertical towers) as being inhibited by occurrence of a strong ambient wind field. Observations and studies in recent years, however, point to some of the most important thunderstorm activity occurring within an environment of strong winds. A quote or two from the Newtons (29) crystalize the more modern concept.

For example,

> "Organized convective systems such as squall lines are generally associated not only with thermodynamic instability but with strong winds aloft as well... continuous regeneration of the large systems must be encouraged, rather than inhibited, by strong vertical shear... the significance of vertical shear is that kinetic energy drawn from the wind field in which a storm is imbedded provides an important additional source which may be put to work in setting off and increasing the vigor of convection."

Of particular significance in reference to the envisioned probable maximum precipitation storm type is another quotation from the Newtons.

> "Other things being equal, the larger the diameter of a cloud system... the greater can be the relative motions between cloud and environment as well as the induced hydrodynamic pressures. Thus, the tendency for the tops of cloud columns to be bodily drawn away from the bases, inhibitory to the development of small clouds... is less pronounced in large clouds." (Underlining ours.)

Thus, one might speculate that in a "cluster" of thunderstorms in the envisioned PMP situation the in-cloud shear may be only a very small percentage of that prevailing in the environmental wind field.

Simpson (13) particularizes the thunderstorms-with-wind concept for the Hawaiian Islands when he concludes

> "...Wind and rainfall maxima in some kona storms have been associated with one or more squall lines or relatively narrow north-south zones of strong convection. These usually produce thunderstorms, which otherwise occur infrequently in Hawaii... Both rainfall and winds (underlining ours) increase outward from the center, become squally in character and reach their peak, in most instances, outside the core of the storm circulation at a radial distance of some 200-500 mi from the low center, depending upon the size of the storm."

Even in the State of Florida where heavy thunderstorms are experienced in prevailing light wind conditions, the exceptionally heavy rains are likely to occur when pronounced vertical wind shear exists. This was the case in a phenomenal rainstorm in southern Florida on January 21, 1957 (30) where the conclusion was made that, "the vertical wind shear was very strong on the day of the heavy rain".

Winds and large 24-hour rains in Hawaii

4.15. The ten heaviest 24-hour rains at Hilo, Honolulu, and Lihue were considered in connection with accompanying wind direction and speed.

These data are shown on figures 4-7, 4-8, and 4-9. The obvious conclusion from these figures is the strong preference for winds with a southerly component, with Honolulu showing 9 out of 10, Lihue 7 out of 10, and Hilo 5 out of 10. The windspeed criterion used here was the fastest mile. Of additional interest is the observation that much of the time the highest fastest mile in these cases was also the highest for that particular month. Since, as figures 4-7, 4-8, and 4-9 show, these heavy rains are also times of thunderstorm occurrence, the preference for thunderstorms in above-normal wind conditions is evident. Figures 4-10 and 4-11 further demonstrate Hawaiian wind-thunderstorm-rainfall associations. The data for these figures comprise the period 1950-1959.

Synoptic climatology of winds associated with wet months

4.16. Rainy months were chosen at Hilo, Honolulu, and Lihue based on the following threshold values: Hilo, 25 inches or more, Honolulu and Lihue, 10 inches or more. Average daily winds were then considered for those days within these wet months on which an inch or more of rain fell. The results are shown on figure 4-12. The lack of trade wind control and prevalence of winds with southerly components are again evident. The choice of wet months was in accordance with the observation that prevailing regimes (larger scale) appear to "set-the-stage" for heavy Hawaiian rainfall.

Wet and dry months compared

4.17. In order to further establish the wind-rain relations for the Hawaiian Islands a comparison was made of wet and dry months using data for Hilo, Honolulu, and Lihue. Various techniques were used with frequency tabulations of wind direction versus rainfall as presented in the supplements to the local climatological data for these stations. A summarized comparison of the wet and dry month winds is shown on figures 4-13 (Hilo), 4-14 (Honolulu), and 4-15 (Lihue). The wettest and driest months for the 1956-1959 period are summarized on these figures. The wind summaries from the Local Climatological Supplements (28) were totaled for the four quadrants and plotted for the wettest and driest months for each station. The pertinent data that comprised figures 4-13, 4-14, and 4-15 are listed in table 4-2. Since the readily available data were for a rather abbreviated period, no strongly contrasting rainfall amounts were available for some months.

From the figures shown, plus others not shown, the following pertinent conclusions were made.

(A) Honolulu and Lihue

(1) Generally, strong northwest winds are rain-inhibiting, north through east are dry, while winds from the other quadrants are rain-favoring, particularly winds with significant southerly components (indicative of disturbed trades).

(2) Both wet and dry months have primary modal directions in the northeast quadrant. The wet month, however, has a secondary mode from a southerly quarter with the primary mode diminished in importance.

Table 4-2

DATES AND AMOUNTS OF PRECIPITATION USED IN FIGURES 4-15, 4-16, AND 4-17

				Station			
		Hilo		Honolulu		Lihue	
Month		Year	Pcpn (Ins.)	Year	Pcpn (Ins.)	Year	Pcpn (Ins.)
Jan.	Max.	1960	25.95	1957	13.33	1957	16.14
	Min.	1958	2.91	1958	0.50	1960	0.97
Feb.	Max.	1960	15.97	1958	5.15	1957	7.09
	Min.	1958	5.41	1960	0.51	1958	2.17
Mar.	Max.	1959	7.83	1958	18.51	1960	9.72
	Min.	1957	3.90	1957	0.01	1957	0.30
Apr.	Max.	1957	17.50	1957	1.56	1957	2.15
	Min.	1958	4.99	1960	0.01	1958	1.10
May	Max.	1960	11.70	1960	3.85	1959	2.80
	Min.	1957	6.32	1958	0.24	1957	0.54
Jun.	Max.	1960	6.73	1958	0.21	1957	1.90
	Min.	1959	3.12	1959	T	1959	0.69
Jul.	Max.	1957	13.27	1958	0.88	1958	4.36
	Min.	1959	5.57	1959	0.28	1956	0.75
Aug.	Max.	1957	26.50	1959	3.08	1959	8.13
	Min.	1959	7.48	1957	0.37	1960	0.87
Sep.	Max.	1960	12.00	1959	0.88	1960	4.58
	Min.	1956	4.03	1957	0.07	1957	0.46
Oct.	Max.	1958	14.64	1958	2.88	1956	9.17
	Min.	1959	9.26	1957	0.11	1957	1.55
Nov.	Max.	1959	27.03	1956	7.24	1957	6.94
	Min.	1957	12.30	1958	0.06	1958	0.60
Dec.	Max.	1957	19.71	1957	2.84	1960	8.49
	Min.	1958	2.86	1959	0.39	1958	2.85

(3) The decreased trade control is obvious for Honolulu for significant March and November data of figure 4-14 (table 4-2). It is perhaps particularly significant that even though nearly all of Honolulu's March 1958 rain fell during a small portion of the month, nevertheless, the prevailing monthly wind regime distinguishes itself markedly from the dry month.

(4) The increased southerly component and concomitant lessening of trade control is obvious in the wet (1957) versus dry (1960) January wind data for Lihue (figure 4-15).

(B) Hilo

No obviously significant conclusions were indicated by Hilo's surface winds. For this reason, a separate study was made of Hilo's upper air winds in five heavy 24-hour rain cases as follows:

(1) March 9-10, 1953--9.18 inches
(2) December 8-9, 1954--10.10 inches
(3) December 10-11, 1954--8.32 inches
(4) February 25-26, 1956--10.63 inches
(5) November 1-2, 1959--15.59 inches

Table 4-3 summarizes the southerly components of the wind (in meters/sec) for layers in these storms. The pertinent conclusion from these data is the fact that the largest Hilo rainfall is the one with the most pronounced southerly component of wind.

Table 4-3

MEAN SOUTHERLY COMPONENT OF WINDS FOR SIGNIFICANT HILO RAINS

Southerly Component Wind (m/s)

	03Z			15Z		
Storm Data (mb)	1000-850	850-700	500-300	1000-850	850-700	500-300
3/9/53	3	4	1	5	3	2
3/10/53	2	5	13	1	3	M
12/8/54	-	-	3	-	-	< 1
12/9/54	-	-	4	-	-	< 1
12/10/54	-	-	11	-	-	12
12/11/54	-	-	3	-	-	-
2/25/56	3	4	10	7	5	6
2/26/56	< 1	-	1	3	< 1	1
11/1/59	6	9	15	6	7	7
11/2/59	4	8	12	2	3	-

A generalization of the above indications from the stations considered would be that the PMP wind will veer into more of a southerly direction from the prevailing trades. In order to assess the extreme deviation in the trade regime required to bring the PMP to the most sheltered (leeward) regions, such as the kona region of Hawaii, consideration was given to the unusual storm of January 16-19, 1959. Heavy rains were observed from this storm establishing records for one day amounts at many kona stations. This storm developed strong pressure gradients that resulted in strong south to southwest winds particularly at intermediate and high levels with Mauna Loa Observatory reporting sustained speeds of 85 miles an hour. For probable maximum rainfall considerations in the kona region of Hawaii, above-normal winds from a southwesterly direction will prevail.

Generalized conclusions

4.18. From the various wind-rain studies enumerated above (plus consideration of additional discussion in IV-B), the two most pertinent conclusions are:

(1) The probable maximum precipitation storm wind may vary from northeast through south to southwest. Slopes facing these wind directions are potentially full windward slopes in a PMP storm.

(2) Windspeeds in the probable maximum storm will likely be above normal but not necessarily extreme.

D. HURRICANES AND HAWAIIAN PMP

Introduction

4.19. The climatological records were surveyed for tropical storms and hurricanes in the eastern North Pacific. The Hawaiian Islands directly experienced a hurricane for the first time during recorded history in August 1950, followed by 3 more before 1960. The relationship of the PMP in the Hawaiian Islands to hurricanes is approached on the basis of (1) what can be deduced from the observed Hawaiian hurricane data and (2) what can be deduced from considerations of tropical storm and hurricane records in other parts of the world. The conclusions reached are: (1) The potential for extreme rains in hurricanes that affect the Hawaiian Islands is no greater than in some other types of cyclones, for example, extreme kona storms. This applies both to the basic non-orographic PMP and to the areas of orographically-increased PMP. (2) Storm types other than hurricanes because of their frequency are much more likely to produce the extreme rains.

Hawaiian hurricanes and tropical storms

4.20. The four significant hurricanes that have affected the Hawaiian Islands are:

(1) Hurricane "Hiki" of August 1950
(2) Hurricane "Konoa" of July 1957
(3) Hurricane "Nina" of December 1957
(4) Hurricane "Dot" of August 1959

There have been some lesser tropical cyclones of which the more recent and prominent were in August and October 1958. Other hurricanes may have come relatively close to the islands in earlier years but documentation is poor.

The first salient point is that there does not appear to be more than a slight correlation between the strength of the wind and the intensity of precipitation. Hurricane Dot had by far the highest winds, 125 mph, but the rain was less intense than in the 2 tropical storms in 1958 already alluded to. This is in line with experience in other parts of the world where hurricane flood disasters have occurred from rain released after the storm had diminished to well below hurricane intensity. See for example, "National Hurricane Research Project Report No. 3 (31).

The second salient point is that the off-season hurricane "Nina" of December 1957, produced the largest published daily rainfall amount. This suggests, though of course it does not prove, that the cool-season dynamics as in other types of storms, is a significant factor and that there is some tendency for mid-season hurricanes to have their rain-producing potentials limited by some subsiding air from the persistent subtropical High. In any case, there is no strong empirical evidence that warm season hurricanes around the Hawaiian Islands are likely to approach the intensity and size of those experienced in the western Pacific or Caribbean.

Most probable hurricane threat

4.21. From the indications of par. 4.20 and from the general knowledge of storm behavior in the Hawaiian Islands and of hurricane rainfall behavior elsewhere, it appears that the greatest rainfall threat from a tropical storm for the small basins of the Hawaiian Islands is for the storm to occur "off-season" and take on non-hurricane characteristics. Such a storm, moving slowly, would produce TIFCA of the PMP type and is safely enveloped by the rainfall values that have been assigned to this situation. Whether the cyclone was of a "hurricane" or "non-hurricane" type would become an academic and perhaps difficult-to-decide question.

The fully developed hurricane - indications from other parts of the world

4.22. The release of orographic precipitation from a fully developed hurricane, releasing rain with great efficiency, is one of the more remote storm possibilities for the Hawaiian Islands, but one which should be evaluated. Conveniently this can be done by reference to another PMP study. The Cooperative Studies Section of the Weather Bureau has prepared a probable maximum precipitation report for Puerto Rico and the Virgin Islands (32) at very close to the same latitude as the Hawaiian Islands but, quite distinct from the Hawaiian Islands, in a zone of prevailing tracks of major hurricanes. Most of the maximum station 24-hour precipitation amounts in Puerto Rico have occurred with hurricanes. The non-orographic 24-hour point PMP in non-orographic coastal regions is concluded to be 40 inches. This is derived by considering both a hurricane converging wind model and statistical analysis of point rainfall data. Thus, recognizing that the hurricane rainfall potential in non-orographic regions is less in Hawaii than in Puerto Rico, the 40-inch base value that has been adopted for Hawaii from other considerations is judged to safely include hurricane effects.

Now turning to orographic regions, in Puerto Rico the PMP is increased on the mountain slopes from the coastal values by reference to an orographic windflow model of wind ascending the slope while still maintaining the non-orographic convergence effect. Direct use of the model leads to computed 24-hour point PMP centers of 70 inches but these are cut back to 60 inches (over somewhat larger areas) for the final recommended PMP in the report (32). Applying this same hurricane combined convergence and orographic wind model to the Hawaiian Islands, then reducing the answers qualitatively to allow for (1) the fact that the maximum hurricane wind potential is less in Hawaii than in Puerto Rico and (2) the "cornering effect" whereby wind flows around instead of over isolated peaks, the potential for orographic PMP in Hawaii in a hurricane of this character is found to lie within the values recommended from other considerations from more frequent storm types.

Chapter V

24-HOUR POINT PROBABLE MAXIMUM PRECIPITATION

Introduction

5.01. This chapter deals with the derivation of the general level of the Hawaiian PMP and the adjustments of this general level for depletion of moisture and for intensification due to ground slope in order to arrive at 24-hour point PMP index maps. Considerations are also given to seasonal variation of the probable maximum precipitation. Statistical estimates are also considered.

The approach used in this report (i.e., adjusting non-orographic rainfall for orographic effects) requires an evaluation of the effects of orography on rain intensity. To know these effects with a large measure of certainty must await the establishment of dense rain gage networks in appropriately chosen orographic regions. What is known now is that vertical motion resulting from ground slope can and does intensify precipitation. It is also known that heavy rains require much moisture, so that, if the moisture supply is drastically reduced by intervening mountains or upwind barriers, the capabilities toward producing heavy rainfall are thereby reduced. In this chapter, empirical rain-intensification-for-ground-slope curves are developed which, in combination with depletion of rainfall for loss of moisture column, result in adjustments for the base non-orographic probable maximum precipitation.

A. NON-OROGRAPHIC PROBABLE MAXIMUM PRECIPITATION

World non-orographic extreme rains

5.02. Record 24-hour rainfall in low-level geographic settings with little or no orographic effects help much to establish a general level for maximum precipitation. The record 24-hour rainfall for the Gulf of Mexico Coast region of the United States occurred at Yankeetown, Florida in September 1950. (38.7 inches in 24 hours.) Another phenomenal 24-hour rain occurred at Kadena Air Force Base, Okinawa in September 1956 (33).

No orographic effects of consequence (in the sense of contributing to vertical motion), were possible in the 42.2 inches of rain that fell at Kadena Air Force Base in 24 hours. Thirty-eight inches of rain fell in 18 hours on September 8 in this storm. The higher moisture charge and the geographical location of Okinawa (far removed from any rain-inhibiting effects of the subtropical high pressure), are suggestive that Hawaii's probable maximum 24-hour precipitation is to be somewhat less than this extremely heavy Okinawa rainstorm. Actually the 42.2 inches at Kadena Air

Force Base in 24 hours is just about the same as the 24-hour probable maximum precipitation for the Gulf Coast region of the United States (34) where, once again, maximum moisture charge is a little higher than that possible in the Hawaiian Islands.

It is instructive to compare the observed maximum-of-record daily rains in the Hawaiian Islands with the above values. The maximum Hawaiian Island values (all of which have some orographic contamination), are:

1. Honomu, Hawaii, which reported 31.95 inches on February 20, 1918.
2. Laupahoehoe, Hawaii, which reported 30.50 inches on December 24, 1901.
3. Kilauea Sugar Plantation, Kauai, which reported at least 38 inches in 24 hours (6) on January 24-25, 1956.

It is possible that the storm of April 1-2, 1961 (par. 4.12 and fig. 5-1), may also fall in the category of having produced rainfall in excess of 30 inches in a day.

Enveloping P/M ratio curve

5.03. Additional consideration for the establishment of the general level of non-orographic PMP is an envelope of ratio of precipitation to moisture (in a vertical column of the surrounding air). The enveloping precipitation/moisture ratio (P/M) curves are indices of the highest observed efficiency of the storm processes, exclusive of orographic, which convert water vapor to precipitation. For a thorough discussion of the P/M ratio concept the reader is referred to chapter IV of Hydrometeorological Report No. 36 (1). The enveloping P/M curve for point precipitation for the Hawaiian Islands is shown in figure 5-1. Mostly, daily rainfall values with a lesser quantity of shorter duration values were used in determining the enveloping curve. All published daily values of 20 or more inches were considered. Many of these were obviously orographically contaminated. Two of these orographically contaminated points are shown as points 10 and 11 on figure 5-1. Point number 12 is considered as having only slight orographic contamination, while point number 13 is considered non-orographic. The curve at the 24-hour duration is placed slightly below point 12. Otherwise, the curve is drawn close to the Moanalua Valley, Oahu, 15.2 inches in 3 hours (point 5) and the 6 inches in 1/2 hour, for Kilauea Plantation (point 2). This represents some maximization since both of these values are likely somewhat orographically contaminated. High values observed in the April 1961 (35) storm are also plotted (points 4, 6, and 8), although the orographic contamination in these values may be substantial. Additional data used in shaping the final curve consisted of numerous additional rains (10 inches in 24-hour caliber), which indicated a 6- to 24-hour ratio of 0.60 to be a reasonable figure.

Establishment of 40-inch/24-hour point probable maximum precipitation

5.04. A 40-inch/24-hour base non-orographic probable maximum point precipitation value was based on the following considerations (covered in 5.02 and 5.03):

(a) The established value is in line with extreme observed world-wide non-orographic values in tropical and semitropical regions with due consideration for Hawaii's location and limitations on moisture availability.

(b) The established value envelops maximum observed rainfall values in Hawaii by a suitable allowance.

(c) The established value is close to that obtained by the product of the enveloping P/M ratio and appropriate cool-season moisture.

B. DEPLETION FOR MOISTURE

5.05. Established Hydrometeorological Section procedure for adjusting storms for intervening mountains (i.e., upwind barriers, etc.), has been to reduce the rainfall in proportion to the theoretical depletion of precipitable water appropriate to the 1000-mb dew point and model used. The depletion of rainfall due to depletion of moisture used in this report is shown in figure 5-2 and is based on a saturated sounding with a 1000-mb dew point of 73°F.

C. OROGRAPHIC INTENSIFICATION FOR GROUND SLOPE

Introduction

5.06. An estimation of the orographic intensification of rainfall to be expected for subtropical mountainous islands of limited extent, was based on a combination of judgment and a limited amount of observed data. Prior to explaining the basic data that helped to determine what the orographic-intensification-for-slope factors ought to be, some comments on the approach are instructive.

What are required are estimates of intensification effects on subtropical islands with relatively isolated mountain peaks or ridges of limited horizontal extent as is indicated in chapter II. An extended formidable barrier such as the Sierra Nevada of California is not very applicable to the Hawaiian orographic problem. In many situations, much of the air flowing normal to such a formidable barrier is forced to rise and flow over. For mountainous islands, such as the Hawaiian group, theory and reason dictate and experience confirms that significant airflow is diverted around those islands where the mountains are tall enough to present a real obstacle. A recent three-dimensional windflow model study in California (36) showed that, at times, diversion of air may be significant even for the formidable barrier.

The derivation of orographic intensification factors below (par. 5.07), is an attempt to provide an answer to the problem of how much of a given column of moisture may be lost but compensated for by a given ground slope. The results must take into consideration indications of variations due to the character of the ridges involved. For a typical extended high ridge, precipitation evidently increases to some point above 5,000 feet. The maximum observed 24-hour rains for the Sierra Nevada in California shows such a relation. See, for example, figure 2-6 of Technical Paper No. 38 (37). For a given weather situation, in which the stability of the air and other factors are the same, for barriers of equal height and cross section, but of differing horizontal extent, the one with the lesser horizontal extent will be less effective in terms of rain intensification due to airflow over the obstacle.

Therefore, for isolated peaks or ridges of limited horizontal extent, ground slopes as contributors to vertical motion will be able to compensate for the loss of a column of rain-forming moisture only up to a point, which will be at some elevation below that for a comparable extended ridge situation (i.e., like the Sierra Nevada).

Data support for rain-intensification-for-slope

5.07. The data discussed below serve to establish an empirical relation of rain intensification versus ground slope shown in figure 5-6.

A search of the literature for orography-rainfall relations applicable to the Hawaiian Islands pointed to a study of Java, Indonesia, rainfall (38) that included much rainfall data where isolated peaks and ridges of limited horizontal extent predominate. In applying that study to the orographic intensification problem in the Hawaiian Islands, however, it is necessary to consider that the envisioned storm in Hawaii will occur with above-normal winds (par. 4.18).

Figures 5-3, 5-4, and 5-5 are adapted from the Java study. The data presented are based on a study using observed rainfall within elevation bands. The figures, taken in order, represent rains of increasing intensity and demonstrate one feature that is significant for probable maximum precipitation. This feature is the trend for the elevation of maximum precipitation to lower as the rain intensity increases. The character of such a trend should show regional variations. For example, where steep slopes at sea level face the rain-bearing winds, the elevation of occurrence may lower all the way to sea level in the extreme rain case. For Java (figure 5-5), the elevation of occurrence of the extreme rain appears at an elevation of 2,000 feet or lower, but not all the way to sea level. In applying the important above-mentioned trend in the Java rainfall data to the Hawaiian Islands PMP case, an allowance is made for a compensating shift to higher elevations of the maximum orographic intensification because of the higher winds.

The Java data also help to set a limit on the <u>amount</u> of orographic intensification to expect. Considering the mean of the absolute daily maximum rains by elevation bands (see dashed curve on figure 5-4), a maximum intensification for orographic effects of slightly over 30 percent is indicated for the 2000- to 4000-foot intermediate elevation range. Area A on figure 5-6 is meant to represent the Java data. Areas are used on figure 5-6 to represent apparent slope intensification in storms or groups of data. To use points would be presumptuous and would convey the idea that the orographic-rainfall relations used are known with more precision than they are. Randomly selected slope determinations on the isolated peaks resulted in values of 0.20 or steeper. Except for the fact that the envisioned PMP storm would occur in conjunction with above-normal winds, the extreme rain data for Java are judged to approximate Hawaiian Island optimum thunderstorm conditions.

Extreme rains in Hawaii also offer some clues in setting limits on orographic intensification factors. A ratio of the maximum orographically contaminated calendar-day rainfall (31.95 inches at Honomu, Hawaii on February 20, 1918), to the maximum non-orographic daily rain (25.95 inches at Opaeula, Oahu on February 28, 1932), indicates slightly less than a 25 percent orographic component. If exact 24-hour values were known and could be compared for the January 1956 storm on Kauai and the Opaeula storm a larger ratio would probably result. If the moisture charge in the maximum rains is considered a separate ratio (in the manner of the dashed curve of figure 5-4) results in an orographic intensification of around 30 percent. However, this adjustment is not made in view of the uncertainties in comparing only two items of data. The Hawaiian data are represented as area B on figure 5-6.

The heavy observed rains at Cherrapunji, India are also considered in placing the rain intensification curves. The suggested position of the Cherrapunji data is shown as area C on figure 5-6. The interpretation of the Cherrapunji rains is that the amount by which they exceed anything reported from low elevations in the same region is indicative of orographic intensification factors operating so as to compensate for the depletion of at least the moisture equivalent of the lowest 4000- to 5000 feet of a moist-air column.

Rainfall values in orographically controlled Colorado west of the Continental Divide are strongly suggestive of orographic intensification compensating for the equivalent of moisture represented by from 4500- to 6000 feet of a column of air. Daily rainfall maxima for this region are plotted on figure 2-7 of Technical Paper No. 38 (37). These data for Colorado point to approximately the same conclusion reached from the longer duration Cherrapunji data. Effective slopes of 0.15 to 0.20 are quite generally applicable to much of the ridges in Colorado west of the Divide. The Colorado data support area D on figure 5-6. Lack of saturation, less than optimum instability, etc., bias the lower magnitude Colorado rainfall data toward an overemphasis on orographic intensification compared to what would likely exist in the PMP case when less lift, etc., would be required to initiate and/or intensify the rainfall.

A record-breaking rainstorm on May 30-31, 1935 resulted in two approximately equal rainfall centers which differed in elevation of occurrence by 2000 to 3000 feet. This storm is referred to as the Cherry Creek, Colorado storm (39). No ground slopes of consequence exist in the area, but a gently narrowing valley upwind of the higher elevation center is strongly suggestive that forced transverse convergence was a factor. There is presently available no feasible method of objectively evaluating in a quantitative manner the rain intensification effects of a narrowing valley. An estimate which is considered reasonable for the Cherry Creek storm is that the topographic configurations produced rain intensification effects equivalent to those of a ground slope of around 0.10. Area E on figure 5-6 pertains to the Cherry Creek storm.

The final item of empirical data which aided in the determination of orographic rain intensification factors for ground slope is from the Altapass, North Carolina rainfall center in the storm of July 13-17, 1916 (39). Area F on figure 5-6 represents this case. During the heaviest 24 hours of rain of this storm, winds from the south appeared to be effective against a ground slope of approximately 0.10 to the extent of compensating for a loss of moisture equivalent of about the lowest two thousand feet of a moist column of air.

Shape of orographic intensification curve

5.08. It can be reasoned that relatively gentle slopes (i.e., less than 0.05 and perhaps less than 0.10) do not contribute much to the precipitation extreme since dynamic factors tied to a synoptic situation can so easily substitute for the minor vertical velocities that gentle slopes can provide. Also, specifically in the Hawaiian Islands, and generally elsewhere, it is usually found that the steeper slopes are at the higher elevations. However, the higher the elevation, the greater the opportunity for more air to be diverted around a ridge rather than to be forced over. Therefore, the significant contributions to vertical velocity are most likely to be found at the intermediate elevations where slopes (which can be effective over durations measured in hours) of the 0.10 to 0.20 range are common. From the above, for the type of geographical setting of interest, an S-shaped curve for intensification of rainfall due to ground slope is most reasonable, that is to say, the relatively most effective rain-contributing slopes are in the intermediate range.

Conclusions on variations with elevation and slope

5.09. Based on the meteorological reasoning and support in data discussed above (5.06, 5.07, and 5.08), the two rain intensification curves for ground slope were placed as shown on figure 5-6 by the following considerations:

(1) Both the storm and PMP S-shaped intensification curves should indicate zero intensification for level ground conditions, while only slight intensification is indicated for slopes less than 0.10, particularly for the probable maximum case (when dynamic factors may overwhelm effects of gentle slopes).

(2) The data support presented in 5.07 (excepting the Java data), were used to draw the storm S-curve.

(3) The PMP S-curve was then fixed relative to the storm curve by drawing the curve: (a) in a maximizing manner to the Java data (i.e., letting the lower limit of Java slopes account for the observed intensifications which at the same time permitted a limiting compensation for depleted moisture of an additional 1000 feet over and above the observed data); (b) with rates-of-change-of-slope effects similar to the storm curve for the intermediate range of slopes of primary interest. (In this range of intermediate slopes the curves are placed with an intensification factor difference of about 10 percent.)

Application

5.10. The PMP rain-intensification-for-slope curve shown on figure 5-6 is considered a meteorologically reasonable and useful curve for helping to define orographic effects in semitropical islands such as the Hawaiian Island group. Since the adjustment-for-orography procedure considers the two factors of depletion-for-moisture and intensification-for-slope, it is desirable to show the two combined. This is done in figure 5-7, which is a consolidation of figures 5-2 and 5-6. This figure gives a single adjustment in percent to be applied to a basic non-orographic probable maximum precipitation value for a given ground slope and height of terrain that is effective in depleting moisture.

Objective evaluations of rain intensification effects of peculiarities of topography such as narrowing valleys, etc., are not readily obtainable at this time. If peculiar orographic configurations are suggestive of rain intensification, one ought to make some allowance for this by using an effective slope that would be more than the measured slope.

It is hoped that the developed curves will prove useful to others working with orography-rainfall relations. In order to obtain refinements in, and to extend the relationships, much additional sampling of extreme rains in mountainous regions is needed where adequate rain gage coverage has been provided. It should be emphasized again that the intensification factors presented are to be considered applicable primarily to rain durations of up to 24 hours and to topographic forms of the isolated-peak and/or ridge-of-limited-horizontal-extent character. Extended formidable ridges should show more extreme orographic intensification.

D. STATISTICAL CONSIDERATIONS

Statistical estimates of PMP

5.11. A method for deriving what is called a statistical estimate of the PMP has been presented by Hershfield (40). The procedure involves statistical analyses of the series of annual maximum 24-hour rains based on extreme value theory with considerations also given to rainfall variability. In the developed equation, $x_m = \bar{x} + KS_n$, K is the number of standard deviations, S_n, that must be added to the mean of the annual maxima, $\bar{x}$, to obtain a rainfall value, x_m, of a particular magnitude. The highest value of K, which was determined from consideration of much data in many countries throughout the world, was 15 which is assumed to be an upper limit.

The application of Hershfield's "statistical PMP" procedure to the Hawaiian Islands resulted in 24-hour rainfall values ranging from more than 75 inches in some of the rainier, windward locations to less than 20 inches in the more sheltered leeward regions. In a general way the over-all average level of the statistically estimated PMP for low elevations on the Hawaiian Islands helps to substantiate the choice of a 40-inch-per-24-hour general level non-orographic PMP.

The range of the "statistically estimated PMP" for the islands ($75'' < x_m < 20''$) is considered excessive. For dry sheltered areas on the Hawaiian Islands (as well as elsewhere), reasoning beyond statistical estimates of the PMP is required, since many such areas have no recorded storm experience of a type which will produce the PMP. The near-PMP category of storms is not adequately represented in the data to which the statistical analysis is applied. The higher values are considered excessive, probably resulting from statistical analysis of data pertaining to a rainfall regime made up of frequent heavy rains. If an enveloping K value were to be determined from just the population of such rainy regimes throughout the world, it would very likely be less than the adopted value of 15. At least the results in Hawaii suggest this.

Rainfall-frequency determinations

5.12. Extreme value statistical procedures were used by the Cooperative Studies Section of the U. S. Weather Bureau to compute rainfall for the Hawaiian Islands for areas to 200 square miles, durations to 24-hours, and return periods of from 1 to 100 years. These are presented in Weather Bureau Technical Paper No. 43 (41). These statistically determined return-period rainfall values were considered in the determination of the PMP index maps of this report (par. 5.15).

E. DERIVATION OF 24-HOUR POINT PROBABLE MAXIMUM PRECIPITATION

Basic tools

5.13. The data and charts necessary for the derivation of generalized charts of 24-hour point probable maximum precipitation consisted of effective barrier charts, effective slope charts and figure 5-7, which converts barrier and slope effects into a combined percentage adjustment for depletion for barrier and intensification for slope.

Example of derivation of PMP

5.14. The Island of Maui is used as an example showing the derivation of the 24-hour point PMP. Figure 5-8 is the smoothed effective barrier chart for Maui. Areas in the 8000- and 9000-foot range on this island are not considered "effective" barriers since the small-sized areas represented by these elevations can have their probable maximum rainfall drift with the wind from rain-producing moisture columns not intercepted by the high elevation terrain. Figure 5-9 is the effective slope map for the Island of Maui, taking into account the wind direction limits for a PMP storm (par. 4.18).

Adjustments to be applied to the basic non-orographic 24-hour point PMP are obtained from figure 5-7 by use of effective barrier heights from figure 5-8 and effective slopes from figure 5-9. Differences resulting from the use of this procedure and values on the final PMP chart stem from smoothing and other factors covered in paragraph 5.15.

Final smoothed 24-hour point PMP charts

5.15. The final 24-hour point smoothed PMP charts are shown on figures 5-10 and 5-11. Hatched areas represent 40 inches. In deriving the final smoothed charts a subjective evaluation of additional factors was required. The more important of these will be enumerated.

(1) The final charts made allowance for the partial effectiveness of northerly-facing slopes. Although it is unlikely that northerly slopes could be effective for a significant portion of 24 hours of the PMP storm, they nevertheless could be quite effective in augmenting rainfall for a limited period in the PMP storm. Thus the wind criteria of paragraph 4.18 were subjectively modified in regions of pronounced north-facing slopes. The north coast of Hawaii was one such area where allowances were made for the northerly-facing slopes.

(2) Statistically determined 100-year return period rains (par. 5.12), were given consideration in the final shaping of isohyets on the PMP index maps. Ratios of PMP to 100-year rainfall were determined throughout the islands. Where this ratio was less than 2, the PMP was increased, particularly if length of record appeared to result in valid statistical estimates. The area in the vicinity of Mountain View, Hawaii (19.5N;155.1W), is an example of an area where such adjustments were made.

(3) The spillalong and spillover of raindrops were given additional consideration in deriving the final PMP charts. A good example of modifications due to spillalong considerations was around most of the coastal areas on the Island of Hawaii. In such areas the 40-inch general level non-orographic PMP was allowed to prevail several miles inland.

(4) The maximum observed rainfall of record (mainly those of a day's duration), was determined. These values were maximized for moisture charge. Figure 5-12 shows moisture-adjusted values of maximum observed daily rains for the Island of Hawaii. The analysis is based on values from published rainfall data. The consideration of these values also led to some additional modification of the adopted PMP charts. For example, along the northeast coast of Hawaii the PMP was set a little higher than what was indicated by other procedures.

(5) Allowance was made for certain orographic configurations which appeared capable of augmenting precipitation through such processes as forced transverse convergence. An example of where such modifications were required was along the northeast coast of Maui. Only the larger scale and more outstanding of such configurations were considered, however.

Distinguishing characteristics of PMP charts from general climatic charts

5.16. The distinguishing characteristics of the PMP charts compared, for example, with median annual precipitation charts, are the following:

(1) Those steep-slope areas where significant normal wind components are rarely observed have high ratios of PMP values to observed.

(2) Leeward areas (in reference to the trades), in general have high ratios of PMP values to observed. This is due to the rarity of the leeward PMP type storm in Hawaii.

(3) Windward areas (in reference to the trades), such as the northeast coast of Hawaii, have relatively low ratios of PMP to observed precipitation.

F. SEASONAL VARIATION OF PROBABLE MAXIMUM PRECIPITATION

Seasonal variation of maximum moisture

5.17. The adopted seasonal variation of maximum persisting 12-hour dew point is shown on figure 5-13 as curve A. Also shown on figure 5-13 are seasonal curves of dew points for varying return periods. The derivation of figure 5-13 is covered in appendix A. The seasonal variation of maximum moisture is rather modest with a range of 4°F from near 72°F for a maximum 12-hour dew point in March and April to a high of 76°F in September.

Seasonal variation of precipitation

5.18. Figures 3-9 through 3-13 present histograms of mean monthly, maximum monthly, and maximum daily precipitation. These data on the various islands point strongly to the cool-season occurrence of maximum precipitation (par. 3.03 and 3.04).

Several additional figures are presented (figures 5-14 through 5-17), covering rainfall categories from maximum calendar-day rainfall (figure 5-16), to maximum ten-minute and one-hour rainfalls. These figures jointly considered with others such as figures 3-9 through 3-13, point to the November through April season as the period most likely to have maximum rainfalls whether the duration is less than an hour or as much as a month.

Considered in conjunction with the seasonal variation of maximum moisture (figure 5-13), the conclusion is reached that maximum rains do not favor occurrence at the time of maximum moisture. In general, January and March appear to be the months most likely to experience heavy rains.

Instability vs. temperature

5.19. Showalter stability index values (42), were determined for "rain days" at Hilo, Honolulu, and Lihue. A "rain day" was defined as a day with two or more inches of rain. An important result was that these most unstable situations occurred generally with temperatures well below the maximum for the date. For example, in 15 cases in the October through March season with a Showalter Index of -2 or less (i.e., more unstable), the prevailing dew points averaged 8°F below the maximum persisting for the respective dates. (The determination of maximum persisting 12-hour dew points is explained in appendix A.) Since the unstable cases favor heavy rains, again the lack of high correlation of heavy rains with highest dew point cases is indicated.

Conclusion

5.20. Considering the fact that maximum rains occur in months of lower maximum dew points (and temperatures), the most feasible and reasonable conclusion was that there would be no seasonal variation of probable maximum precipitation. The thought here is that other factors operating to enhance precipitation appear to combine in a less efficient manner when the dew points are higher. Thus, the derived probable maximum precipitation is considered applicable without adjustment to the November through April season.

Chapter VI

AREA AND DURATION RELATIONS OF PROBABLE MAXIMUM PRECIPITATION

Introduction

6.01. It is not uncommon in Hawaii for the maximum rainfall for an extended range of durations to occur in the same storm. For example, the largest short duration rain (i.e., the 30-minute duration in the January 1956 storm on Kauai), was part of a storm which also produced the largest 24-hour rainfall for the Hawaiian Islands. A consideration of the largest 6-hour and 24-hour rains at Honolulu, Hilo, and Lihue also showed a strong preference for the maximum 6-hour rains to occur in large 24-hour storms. No significant and consistent regional variations were obvious in the durational ratios suggesting a single durational-depth relation for the islands.

Point depth-duration criteria

6.02. Enveloped Hawaiian Island point rainfall depths were used to define the point rainfall variation for durations up to 24 hours. A convenient means of doing this was to scale ratios of other durations to 24 hours from the P/M ratio curve of figure 5-1; this is valid because "M" is relatively fixed over a number of hours. This depth-duration relation for point rainfall is considered applicable throughout the islands.

24-hour depth-area criteria

6.03. Hawaiian storm rainfall data were used in defining the depth-area portion of the DDA relations. Depth-area analyses were made of storms most of which produced record rainfall values. The following storm periods were considered (using published 1-day, 2-day, etc., rainfall amounts).

1. November 18, 1930 on Oahu
2. March 2, 1939 on Hawaii
3. May 13, 1940 on Kauai
4. November 28-30, 1954 on Kauai
5. January 25, 1956 on Kauai
6. March 5-6, 1958 on Oahu
7. November 1-3, 1959 on Hawaii

Figures 6-1 through 6-4 show the rainfall analyses of the four most recent storms. The results are non-conservative (fast decrease of rain with increasing area), insofar as offshore rainfall was considered a minimum. On the other hand, they are conservative in that the addition of more rainfall values in a particular storm usually yields a more severe reduction with area. This was true for the January 1956 storm on Kauai where an analysis of the 3-day rainfall by Price (43), using additional rainfall data (covering a 3-day period), showed a more severe dropoff with area than the depth-area curve (for 1 day) in figure 6-5, based on less data.

Depth-area relations for durations of 2 and 3 days generally do not differ much from the 24-hour duration. Therefore, in order to make some allowance for depth-area relations in storms which bracketed calendar days, some 2-day and 3-day analyses were used in the seven storm periods considered.

Final selection of the depth-area relation appropriate for Hawaiian rainfall at the 24-hour duration was based on the following considerations.

(1) The adopted curve was placed between a mean and an envelopment of the data from the 7 Hawaiian storms. Based on the fact that the areal dropoff is greater for the more severe storms in the group, the curve is conservative.

(2) Emphasis on the envisioned PMP storm type with thunderstorms in a moist flow was instrumental in the choice of the adopted depth-area curve. Thus, the adopted curve is considered correctly placed more conservatively (less dropoff with area), in regard to southwestern U. S. thunderstorm rainfall relations and more closely approximating the controlling eastern U. S. data where active inflow accompanies maximum thunderstorms.

The adopted 24-hour depth-area relation with supporting storm data are shown on figure 6-5.

Combined DDA relations

6.04. The adopted duration-depth-area (DDA) curves are shown on figure 6-6. The adopted depth-area relation from figure 6-5 controls the 24-hour curve. The depth-duration relation for point (i.e., 1 square mile), is taken from the P/M curve of figure 5-1.

With the 24-hour depth-area and the 1-square mile depth-duration established, possible variations in the remaining DDA relations are quite limited. Maintaining consistency with convergence rain in other regions and giving relatively more dropoff with area to shorter durations were other controls that led to the final combined relationships.

Areal distribution

6.05. The envisioned PMP type suggests that a large variety of isohyetal patterns are reasonable for application to Hawaiian Island basins. The elongated shape of most of the basins suggest an elliptical pattern for the isohyets.

Time distribution (6-hourly increments)

6.06. Observed heavy rains in Hawaii indicate that of the four 6-hourly increments of the 24-hour PMP, the second highest should be placed next to the highest. It is also preferable to place the third highest adjacent to the maximum 12 hours. Samples of the time distribution of Hawaiian rainfall that suggest the above arrangement are shown in table 6-1. These data are for six large storms at Hilo, Hawaii in which, in each case, a 6-hour amount of at least 3 inches was observed. It is to be noted that in 5 out of 6 cases the two highest 6-hourly amounts were adjoined.

Table 6-1

SEQUENCE OF RANKED 6-HOUR RAIN AMOUNTS IN 24-HOUR STORM
(HILO, HAWAII)

	Storm					
Storm Period	A	B	C	D	E	F
	Ranked magnitude of 6-hrly rain amounts (1= greatest, 4= least)					
1st 6-hr	3	4	4	2	4	2
2nd 6-hr	1	2	3	1	3	3
3rd 6-hr	2	1	1	4	1	4
4th 6-hr	4	3	2	3	2	1

Time distribution of hourly PMP increments patterned after observed sequences

6.07. The hourly rainfall amounts observed at the U. S. Weather Bureau Honolulu Airport station in the record-breaking March 1958 storm are shown on figure 6-7. Also are shown hourly increments for the more phenomenal shorter duration rainfall observed at Moanalua Valley, Oahu on November 18, 1930 (point number 5 of figure 5-1). These examples from extreme Hawaiian rains lend support to the reasonableness of established procedures for time distribution within the maximum 6-hour rainfall as, for example, in Civil Engineers Bulletin 52-8 (44).

Chapter VII

DERIVATION OF PMP ESTIMATE FOR A PARTICULAR BASIN

General

7.01. The derivation of a PMP estimate for a drainage basin requires use of the appropriate 24-hour point (i.e., 1 square mile) values from figures 5-10 or 5-11 and the DDA curves (figure 6-6). Stepwise instructions for obtaining estimates for a small and a larger basin follow.

Small basin with uniform hydrologic features

7.02. (1) The 24-hour basin-average PMP is determined by planimetering the area within the basin on the 24-hour point PMP maps (figures 5-10 or 5-11). Considering a hypothetical 15-square-mile basin, we shall assume basin-average 24-hour point PMP to be 38.0 inches.

(2) Ratios determined from figure 6-6 for 6- and 3-hourly increments of PMP and time distribution for a storm are shown in table 7-1.

Table 7-1

INCREMENTAL PMP FOR A HYPOTHETICAL 15-SQUARE-MILE BASIN

Duration (hours)	Percent of 24-hr Index Map (from fig. 6-6)	PMP Rainfall Col. 2x38.0 (inches)	3-Hr Incremental PMP (inches)	6-Hr Incremental PMP (inches)	6-Hr Incremental PMP Arranged in Storm Sequence (inches)	3-Hr Incremental PMP Arranged in Storm Sequence (inches)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
3	40.4	15.3	15.3			1.5
6	55.8	21.2	5.9	21.2	3.3	1.8
9	66.6	25.2	4.0			3.0
12	74.2	28.2	3.0	7.0	7.0	4.0
15	81.3	30.9	2.7			5.9
18	86.7	33.0	2.1	4.8	21.2	15.3
21	91.4	34.8	1.8			2.7
24	95.6	36.3	1.5	3.3	4.8	2.1

Values in 6 and 7 of table 7-1 are arranged in accordance with accepted hydrologically critical time sequences (44).

Larger basin

7.03. With larger basins, particularly where variable within-basin hydrologic features exist the use of uniform distribution of the PMP becomes inadequate. An appropriate isohyetal pattern is required and, as pointed out in paragraph 6.05, an elliptical pattern is suggested. Areal distribution of the PMP involves the following steps.

(1) The elliptical pattern should correspond to the depth-area relationships for the 24-hour depth-area curve of figure 6-6. This elliptical pattern, with isohyets in percent of the central value, is placed in a critical position over the basin. Figure 7-1 shows such a pattern using a major-to-minor-axis ratio of 2.0.

(2) The 24-hour PMP at points is computed by multiplying the percentage values of the pattern by the PMP index values, interpolating as necessary.

(3) The PMP values computed in step (2) are analyzed to give the PMP pattern over the basin.

(4) The average basin-wide PMP is obtained by planimetering the pattern of step (3).

(5) Time distribution of the PMP is in accordance with the procedure shown in table 7-1.

Implicit in the use of a pattern storm is a basin-shape factor which reduces the basin PMP from that assuming uniform distribution. Since extreme precipitation controlled by the envisioned prototype can reasonably result in a variety of isohyetal patterns, it is suggested that large reductions due to this procedure be avoided by choosing a pattern which rather closely fits the basin outline.

APPENDIX A

MAXIMUM MOISTURE CRITERIA FOR HAWAIIAN PMP

Introduction

A.01. It has been customary in the Hydrometeorological Section of the Weather Bureau to use 12-hour persisting surface dew points with a saturated assumption for estimating the total precipitable water in a column. That such a relationship also holds reasonably well for the region around the Hawaiian Islands needs to be demonstrated. It is necessary, therefore, to study the relationship between surface dew points and precipitable water for the Hawaiian Islands to test the validity of using surface dew points for establishing maximum moisture criteria for probable maximum precipitation estimates for the Hawaiian Islands. It is also instructive to compare mean and extreme seasonal precipitable water and dew point curves for selected U. S. stations in other states with those for the Hawaiian Islands,

Comparison of dew point and precipitable water data for the Hawaiian Islands did indicate that in instances of the more significant rains, the use of the surface dew point, with assumed saturation in depth, resulted in fairly good approximations to the actual precipitable water (W_p).

Mean precipitable water considerations

A.02. To obtain an idea of the prevailing mean moisture regime, mean monthly precipitable water values for Hilo were considered. Computations were made of the precipitable water in the layer from surface to 300 mb for the period from July 1950 through December 1959. The results of this survey are shown on figure A-1. Precipitable water curves are also shown for other selected stations (45). The outstanding difference between San Juan, Puerto Rico, and Hilo curves appears to be that during the warmer half of the season the mean precipitable water at San Juan is about 30 percent greater than at Hilo.

Figure A-2 compares maximum moisture curves similar to the way figure A-1 compares mean curves. Hilo's data are from figure 5-13 (curve A), while New Orleans and San Diego's curves are from the Hydrometeorological Section's 12-hour maximum persisting dew point charts (46). While the data here for the different stations are not strictly of the same kind, the comparison nevertheless is instructive as, for example, the greater maximum moisture charge possible at New Orleans compared to Hilo.

Vertical distribution of precipitable water

A.03. Figure A-3 shows values of precipitable water on the basis of percentages of the total below given levels. The data showed practically no seasonal trend in these percentages for the mean Hilo data so the mean curve only is shown on figure A-3. Two additional curves are shown for comparison. One of these is based on a saturated pseudoadiabatic sounding with a 1000-mb dew point of 72 degrees. The other curve is an average of eight Hilo cases where the precipitable water exceeded two inches in each case.

Precipitable water vs. surface dew point

A.04. The data for checking the validity of the assumption of a saturated pseudoadiabatic sounding consisted of two separate categories. First, there were about 250 cases (counting twice-a-day soundings), based on rain days at Hilo, Honolulu, and Lihue. A rain day involved a threshold of 2 inches or more of rain in 24 hours. The second set of data consisted of 60 high dew point cases in which the highest dew points each month at Hilo for the years 1954 through 1958 were used.

In the heavy rain cases the data from upper air summaries (47), were used both for the precipitable water computations and for the accompanying dew point determinations (1000-mb data). Summation of precipitable water was made through 300 mb using increments of 50 mb. Precipitable water tables were then used to determine the precipitable water assuming saturation and pseudoadiabatic lapse rate with the given 1000-mb dew point. Figure A-4 is a plot of these cases with accompanying regression line. The regression equation for the heavy rain cases for estimating the actual precipitable water (Y) from the precipitable water computed from the surface dew point (X), is for all practical purposes $Y = 0.8X$ (the intercept passes very close to zero). It should be noted that for the especially large rainfalls accompanied by relatively high dew points, such as in the March 1958 and November 1959 storms, the saturation assumption comes closer to approximating the existing conditions. This also is evident in figure A-3 by comparison of cumulative percentages of moisture below specified levels for the saturated 72 degree dew point case with the average of the eight cases with precipitable water in excess of two inches.

In the high dew point cases the average of the observed precipitable water for 00Z or 03Z and 12Z or 15Z was correlated with the single maximum 12-hour persisting dew point for that day. The plot of this data is shown on figure A-5. The resulting regression equation is Y (actual W_p) $= 0.28 + 0.57X$ (computed W_p). No seasonal variation in these data could be found.

Results

A.05. When one considers that the prevailing dew points throughout the season in Hawaii approximate the non-winter dew points in much of the United States under the influence of Gulf moisture, then the results are quite comparable. In many states of the United States mainland, cool season dew points quite often underestimate the precipitable water. This is not the case in Hawaii where there is a lack of any real cool season continental air. For the Hawaiian cases there is a consistent overestimation of the moisture on the basis of surface conditions, particularly for the high dew point cases, but also to a lesser extent for the heavy rain cases.

Enveloping dew points

A.06. The highest persisting 12-hour dew point concept was used in this study in deriving an enveloping dew point curve. Data used consisted of Honolulu dew points covering the period 1906-1959 and dew point data for shorter records at Lihue and Hilo. The highest values resulting from the surveys are shown plotted on figure 5-13.

The selection of dew points was made on a semi-monthly basis. The maximum annual semi-monthly dew points for each of the 24 semi-monthly periods were determined. Two uses were made of the data. First, the extreme 12-hour persisting dew point was abstracted for each semi-monthly period for the purpose of determining an enveloping relationship. Second, a probability analysis was made of the data.

Figure A-6 is a sample plot and statistical analysis of Honolulu's dew points (second half of March). The results of the statistical analysis of dew points are shown in the form of curves on figure 5-13 depicting the 2-, 10-, 20-, 50-, and 100-yr return period values. A smooth enveloping curve was drawn to the data for Honolulu with some slight modification by the Hilo and Lihue data. The resulting smooth enveloping seasonal 12-hour persisting dew point curve is shown on figure 5-13 as curve A. For comparative purposes an additional curve is shown on this figure. This curve shows the smoothed seasonal variation of the wet-bulb temperature exceeded 5 percent of the time in the vicinity of Honolulu (5).

In order to determine whether a latitudinal variation in the maximum dew point was in order, a comparison of the temperatures as given by the U. S. Navy Climatic Atlas (5) was made for the latitudinal expanse of the Hawaiian Islands. For most months of the year the large-scale orientation of the isotherms paralleled the islands. This indicated that any latitudinal variation (capable of affecting the inflow moisture charge in a storm), would necessarily be slight. Localized smaller scale variations in the vicinity of the islands are considered relatively unimportant in terms of probable maximum precipitation. Figure A-7 offers more support for not using any latitudinal variation in dew points. The data on this figure represents selected rain cases for which 12-hour persisting dew points were derived for both Honolulu and Hilo. This sample of data indicates no particular bias toward higher storm dew points at either station for the range of dew points considered. A separate study indicated that Honolulu's data often underestimates dew points when middle latitude cool air fronts are present in the vicinity. The derived maximum 12-hour persisting dew point curve on figure 5-13 is considered applicable to all major islands of the Hawaiian group.

When the enveloping dew point curve is put in terms of precipitable water and expressed as a percent of April the following array results:

(Mid-month 12-hour persisting dew points are shown beneath percentages)

	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Percent	104	101	100	100	102	107	113	118	121	119	115	110
Dew Point (°F)	72.9	72.2	71.9	71.9	72.4	73.3	74.5	75.5	76.0	75.6	74.8	73.8

Conclusions

A.07. The use of surface dew points and an assumed saturated column is considered a valid procedure for estimating precipitable water in Hawaiian storm situations and for adjusting actual storms to maximum moisture. A single seasonal maximum 12-hour persisting dew point curve is considered appropriate for use throughout the Hawaiian Islands. This curve is the one designated as A on figure 5-13.

ACKNOWLEDGMENTS

The author appreciates the guidance and advice offered by Vance A. Myers, Chief of the Hydrometeorological Section. Recognition is also made of the many helpful suggestions of Sydney Molansky, George A. Lott, and John T. Riedel of the Hydrometeorological Section.

Much credit is due Dwight E. Nunn, of the Office of Chief of Engineers and to Joseph L.H. Paulhus, John F. Miller, of the Cooperative Studies Section of the U. S. Weather Bureau and David M. Hershfield* of the Agriculture Research Service, Beltsville, Maryland. Coordination of this PMP report with reports of the Corps and the Cooperative Studies Section involved the time and painstaking efforts of these people. The calculations of the statistical PMP referred to in paragraph 5.11 were carried out by the Cooperative Studies Section.

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*Formerly of the Cooperative Studies Section.

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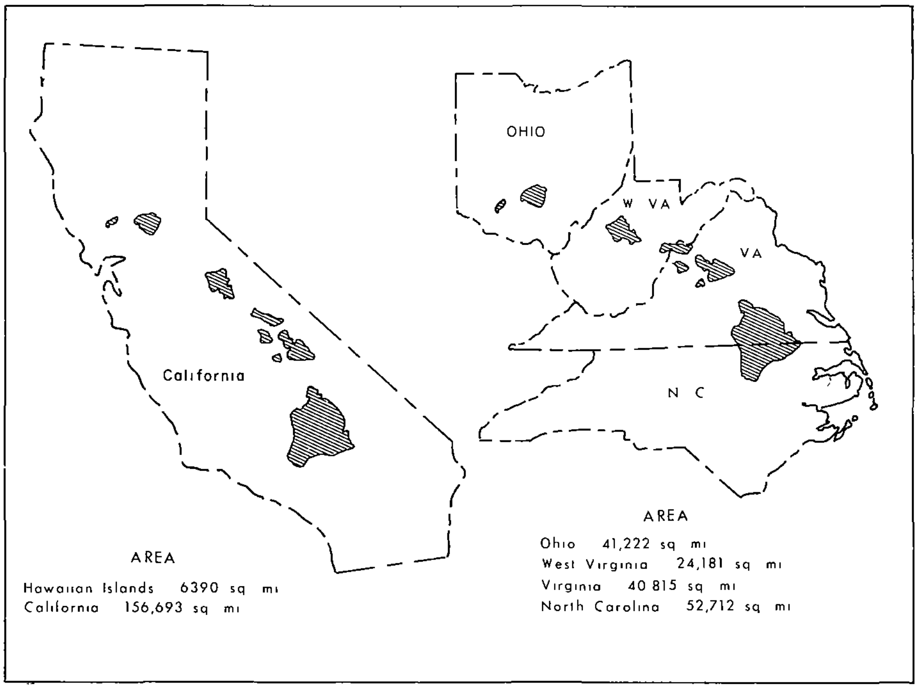


Fig. 1-1. HAWAIIAN ISLANDS - PERSPECTIVE

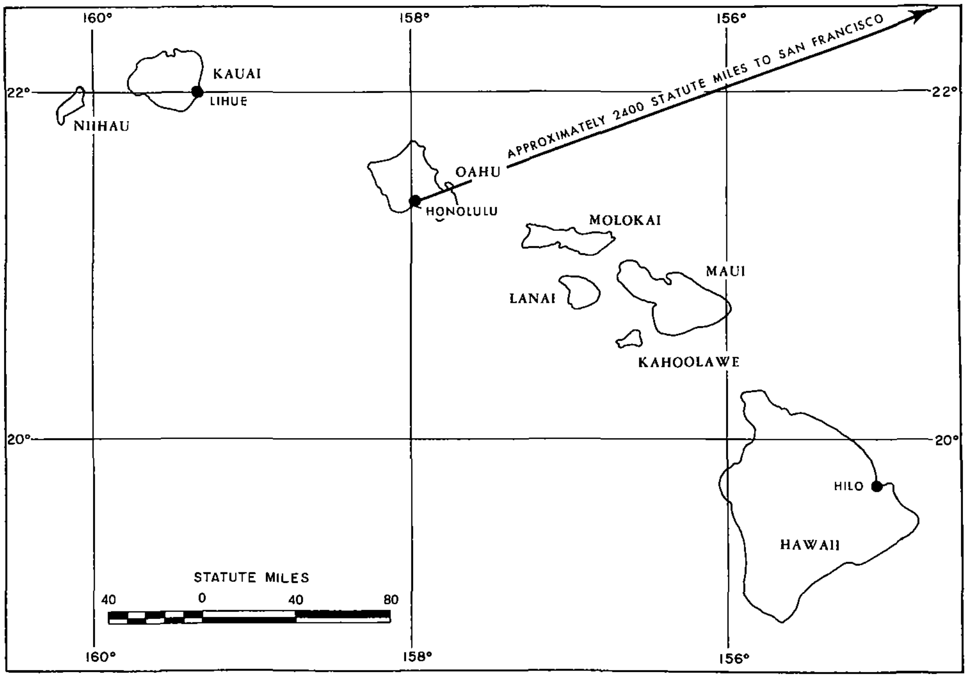


Fig. 2-1. HAWAIIAN ISLANDS - LOCATION CHART

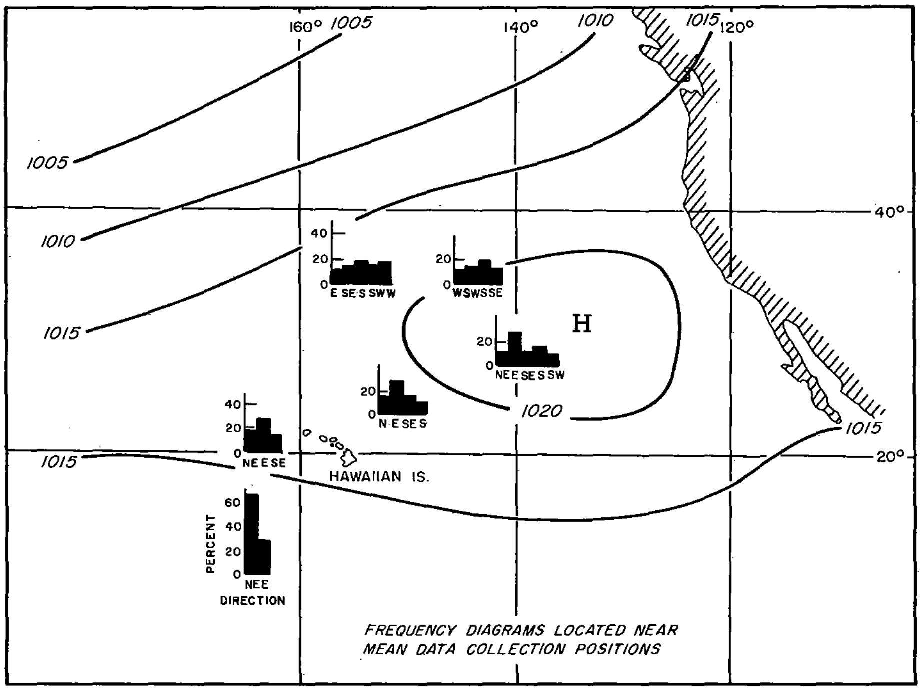


Fig. 3-1. MEAN SEA-LEVEL PRESSURE AND PERCENTAGE FREQUENCY OF SEA-LEVEL WINDS (JANUARY)

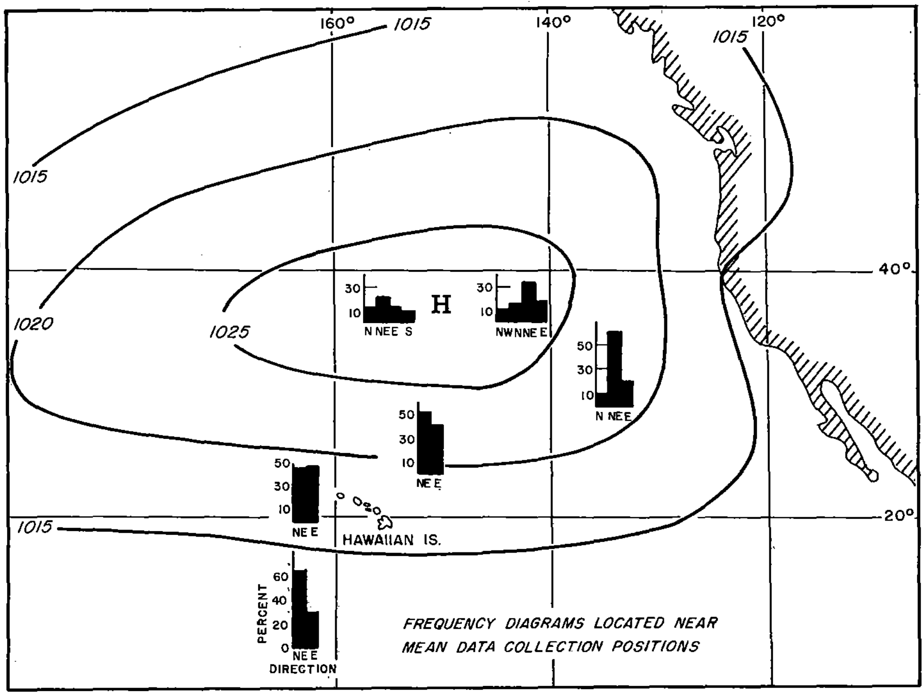


Fig. 3-2. MEAN SEA-LEVEL PRESSURE AND PERCENTAGE FREQUENCY OF SEA-LEVEL WINDS (JULY)

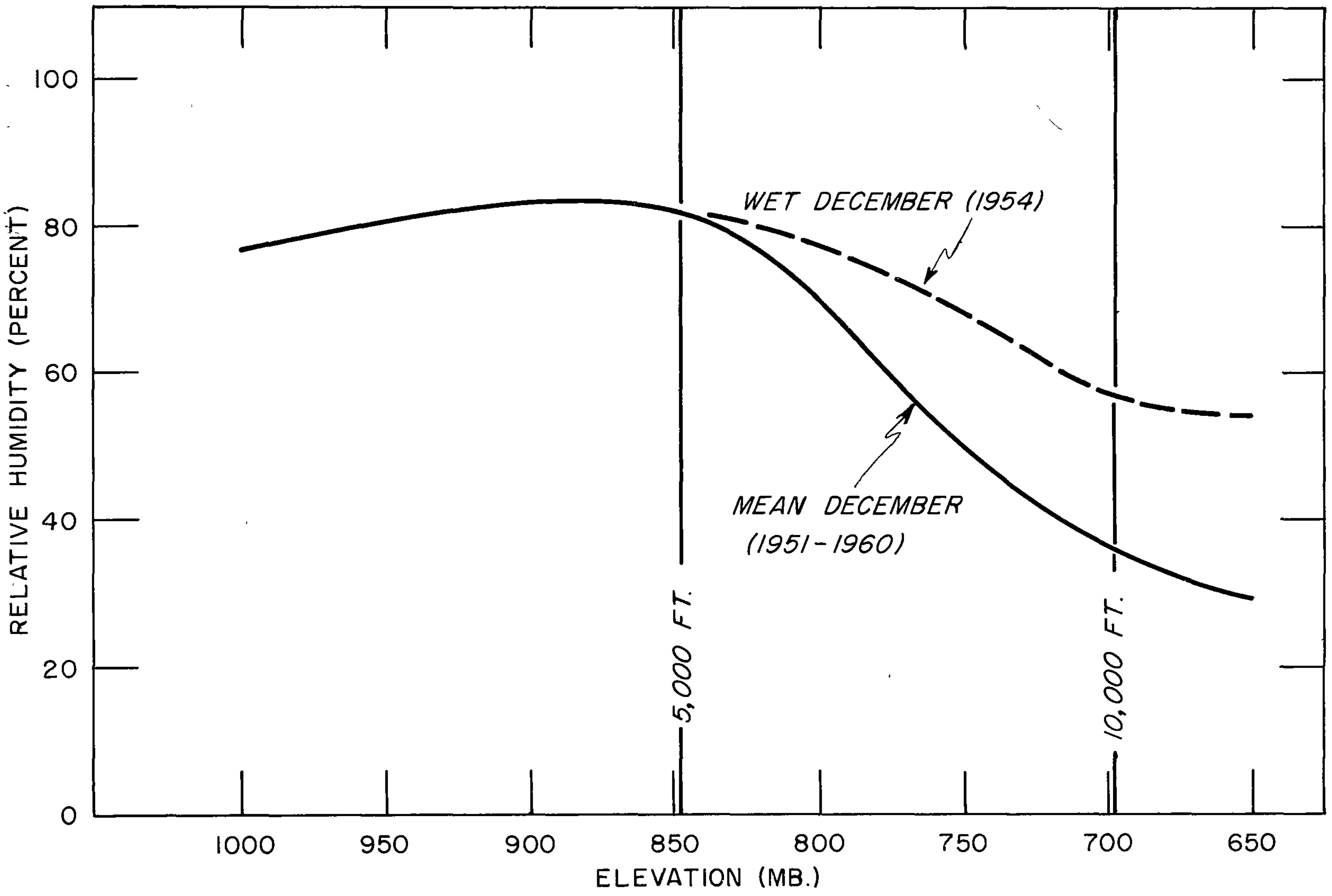


Fig. 3-3. RELATIVE HUMIDITY VS. ELEVATION FOR HILO, HAWAII

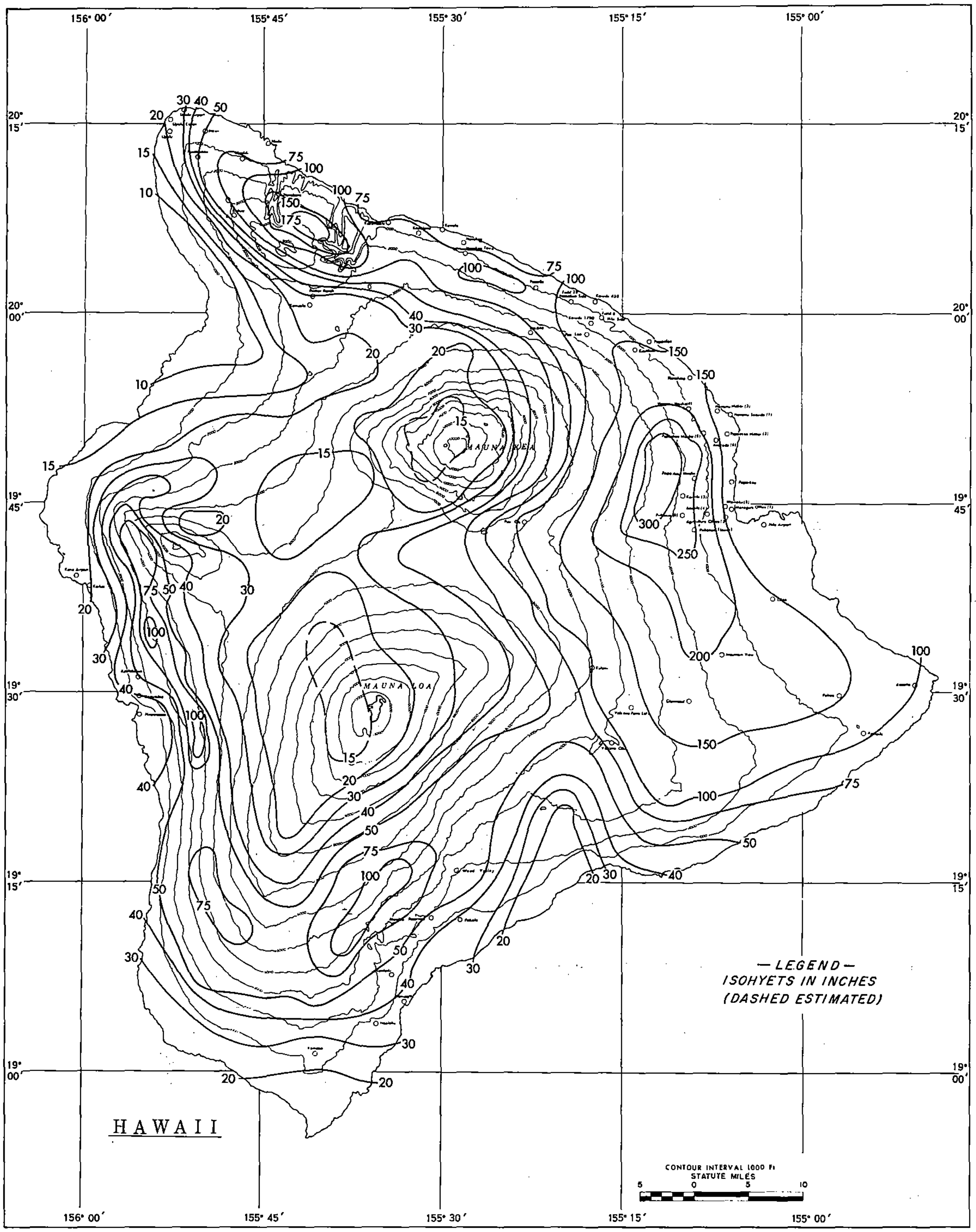


Fig. 3-4. MEDIAN ANNUAL PRECIPITATION - HAWAII

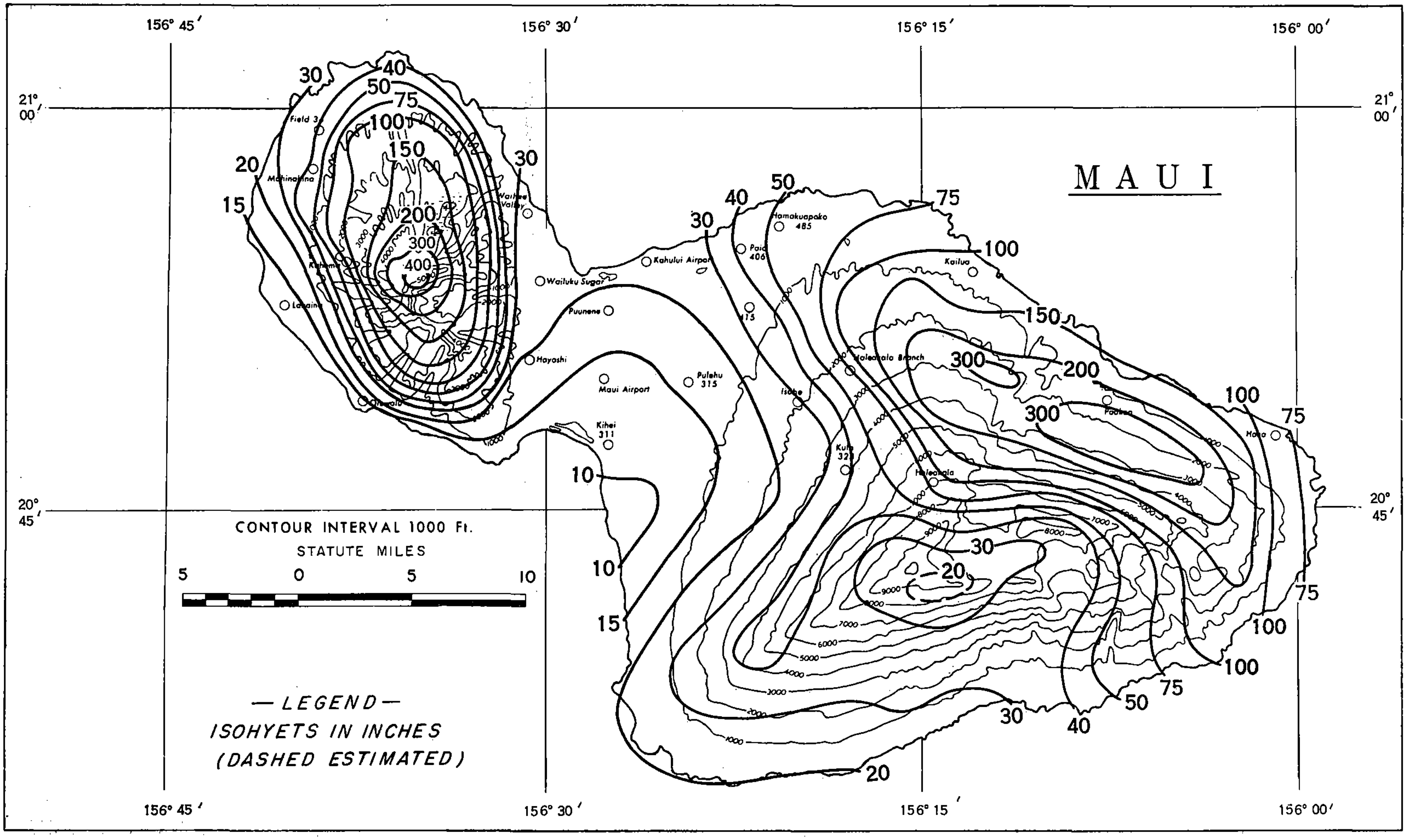


Fig. 3-5. MEDIAN ANNUAL PRECIPITATION - MAUI

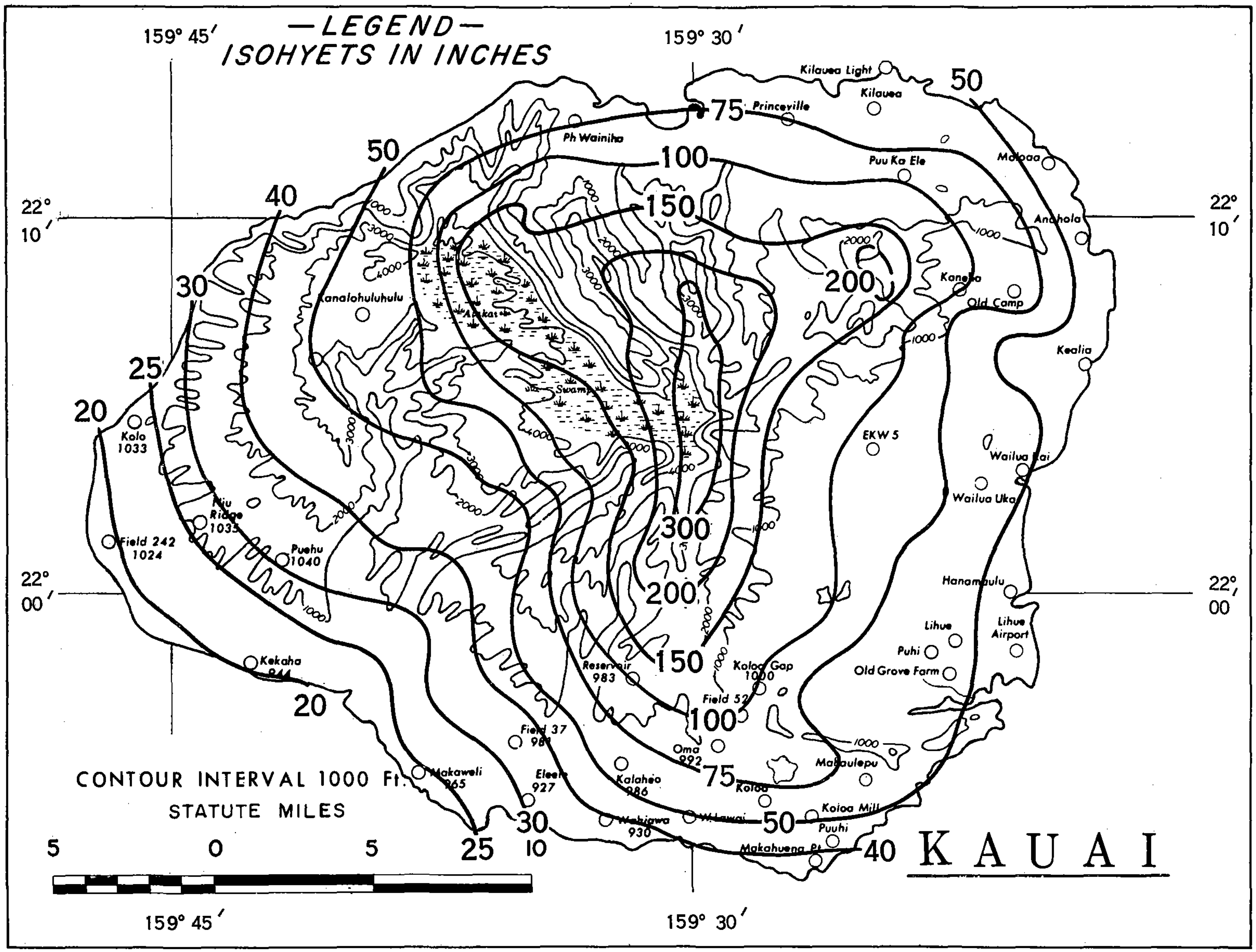


Fig. 3-6. MEDIAN ANNUAL PRECIPITATION - KAUAI

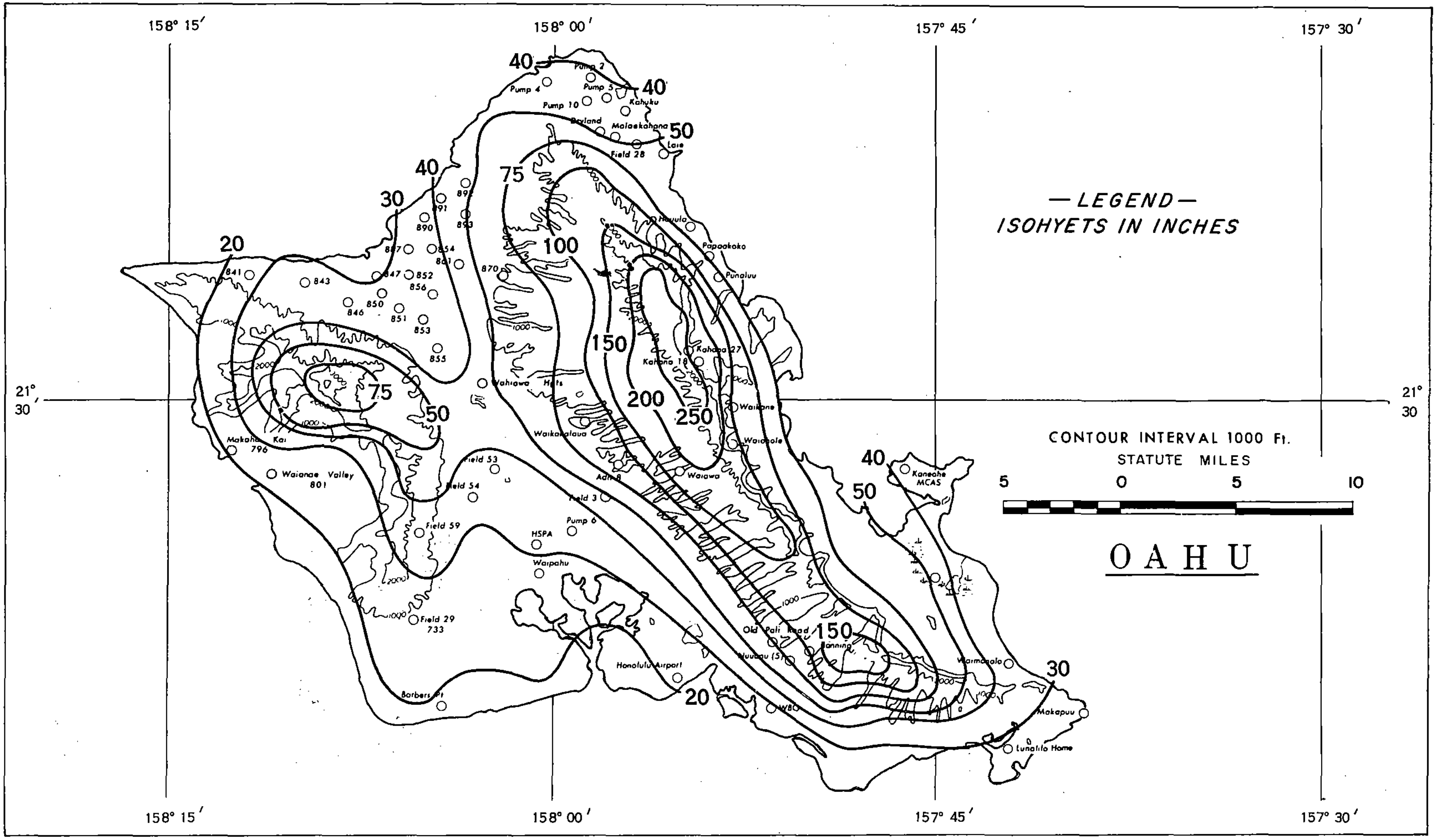


Fig. 3-7. MEDIAN ANNUAL PRECIPITATION - OAHU

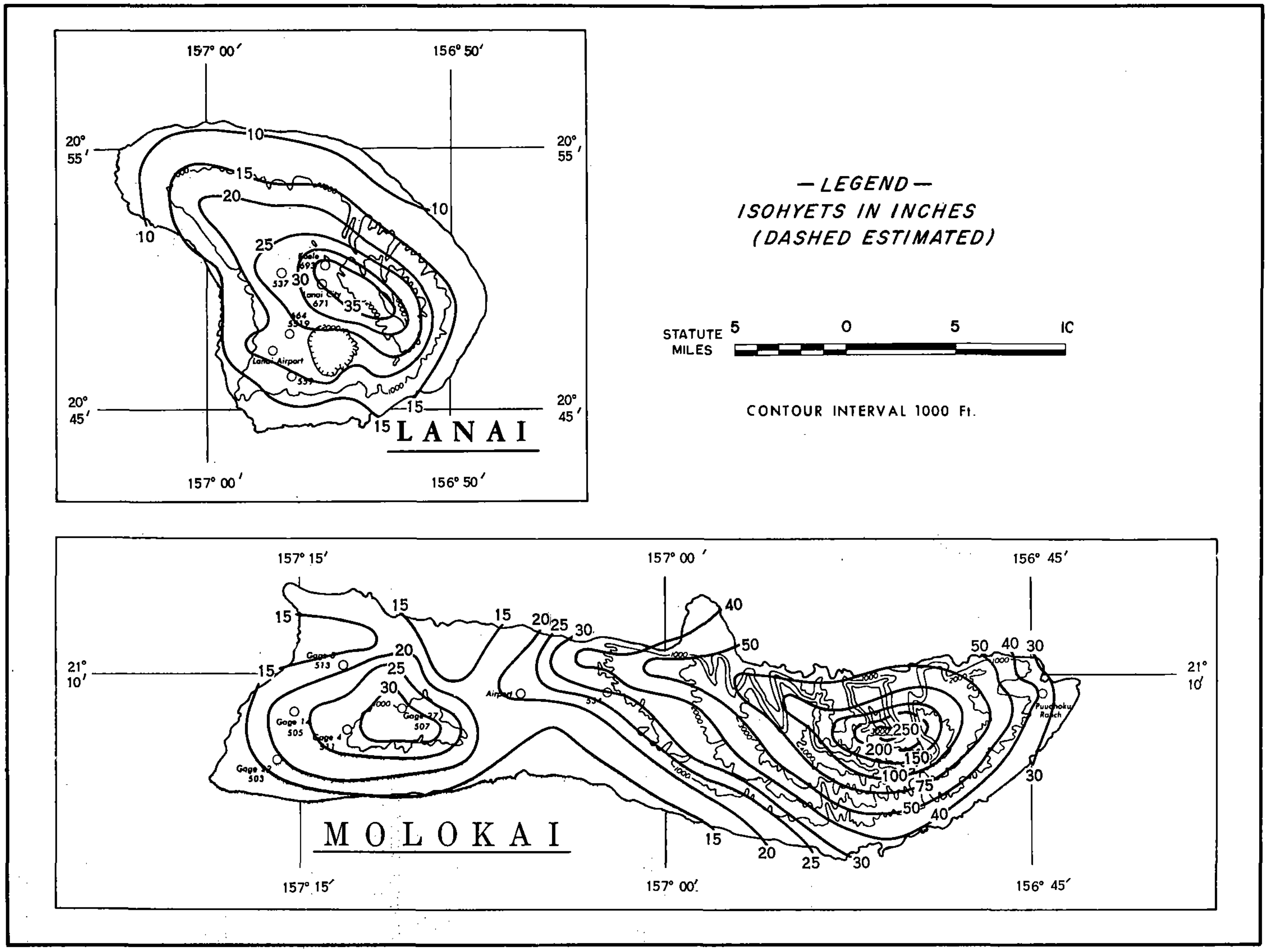


Fig. 3-8. MEDIAN ANNUAL PRECIPITATION - MOLOKAI AND LANAI

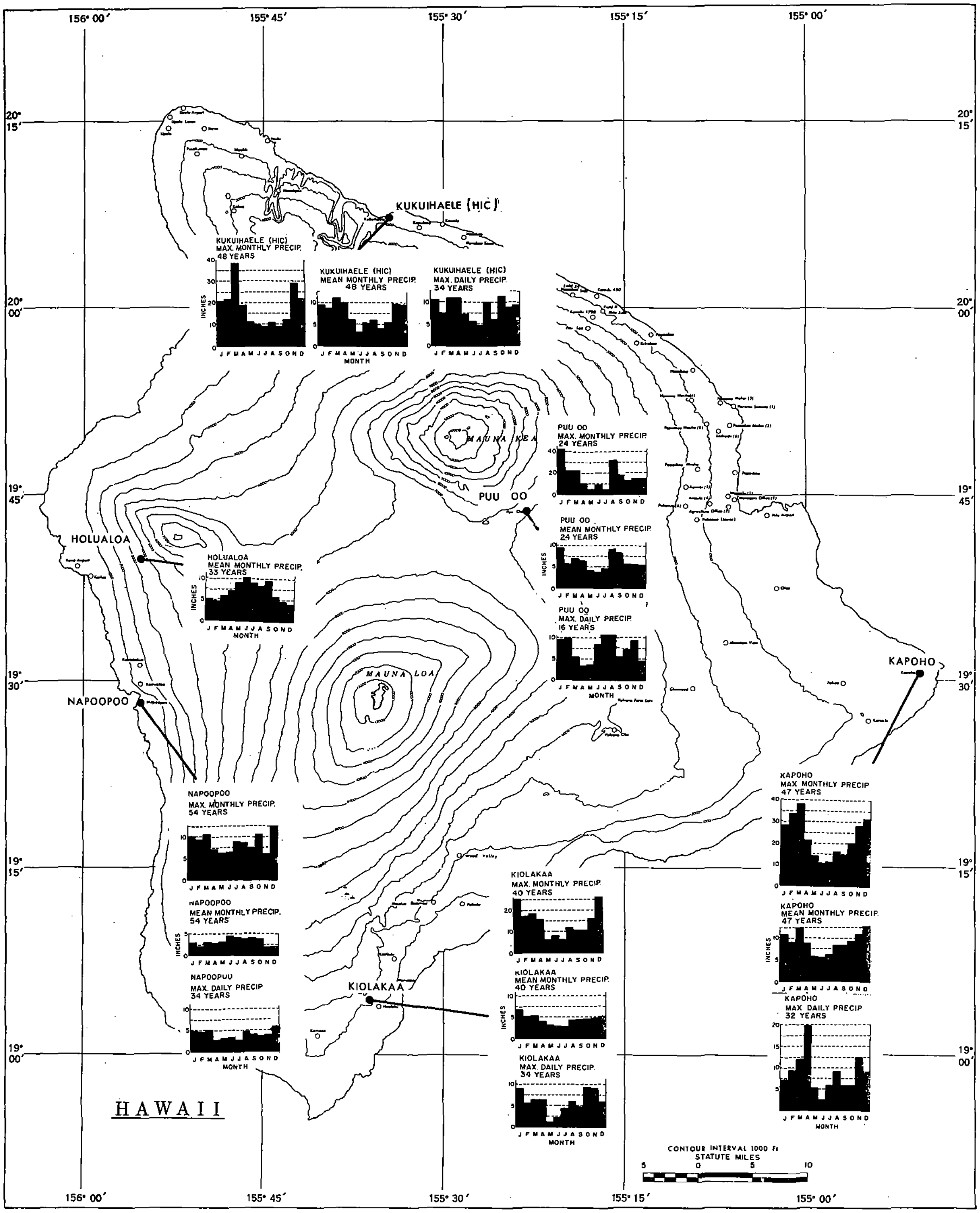


Fig. 3-9. RAINFALL REGIMES FOR SELECTED STATIONS - HAWAII

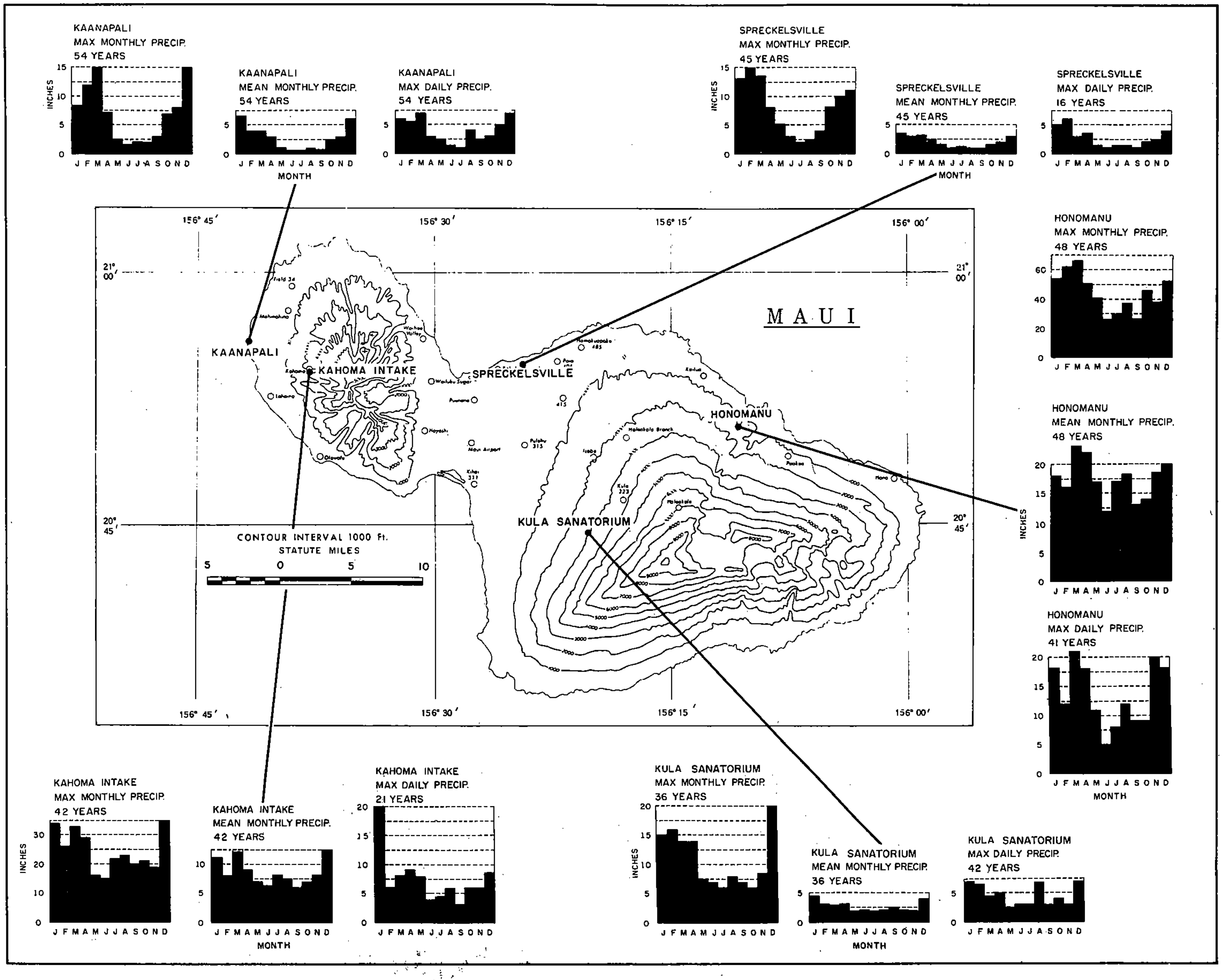


Fig. 3-10. RAINFALL REGIMES FOR SELECTED STATIONS - MAUI

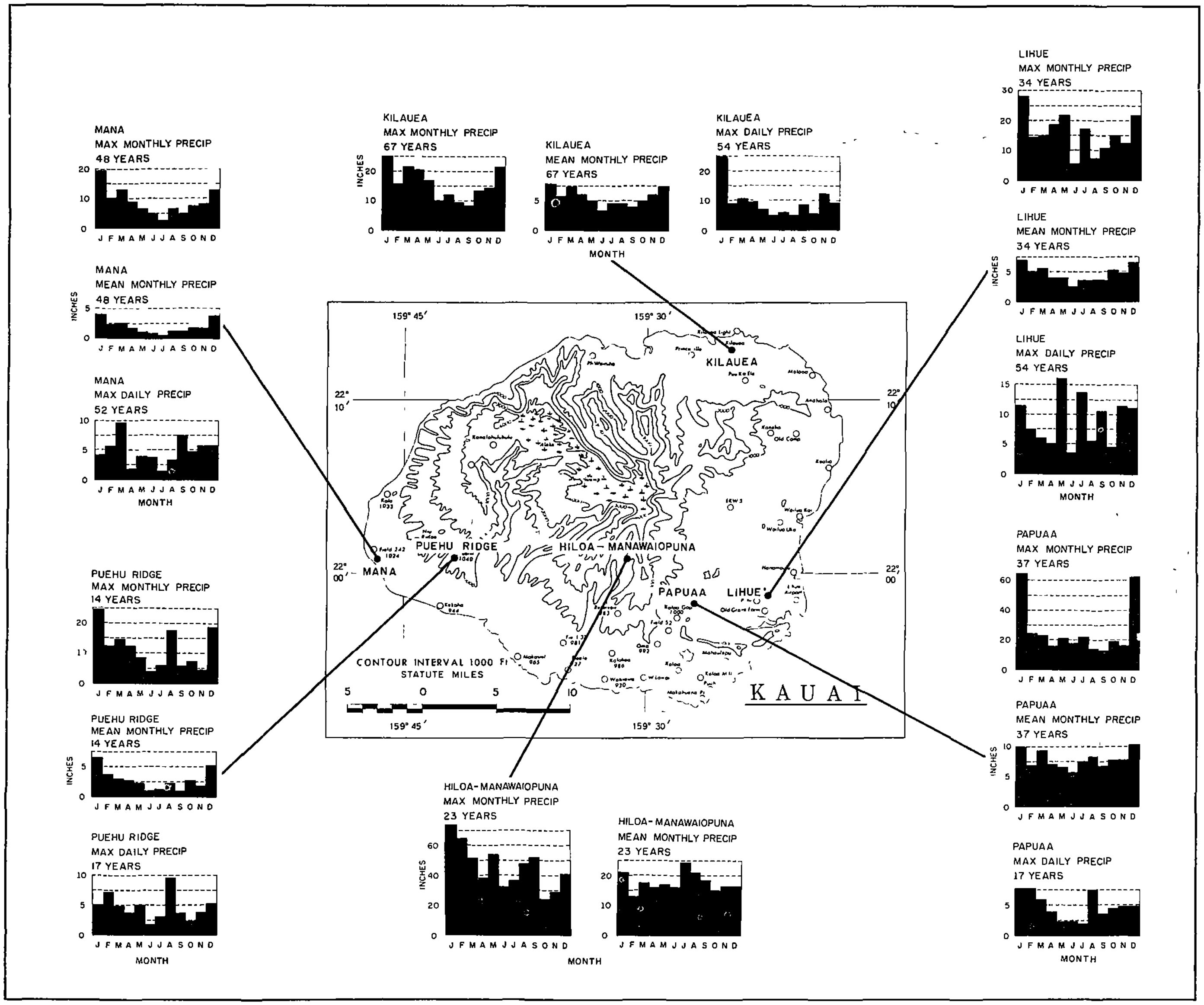


Fig. 3-11. RAINFALL REGIMES FOR SELECTED STATIONS - KAUAI

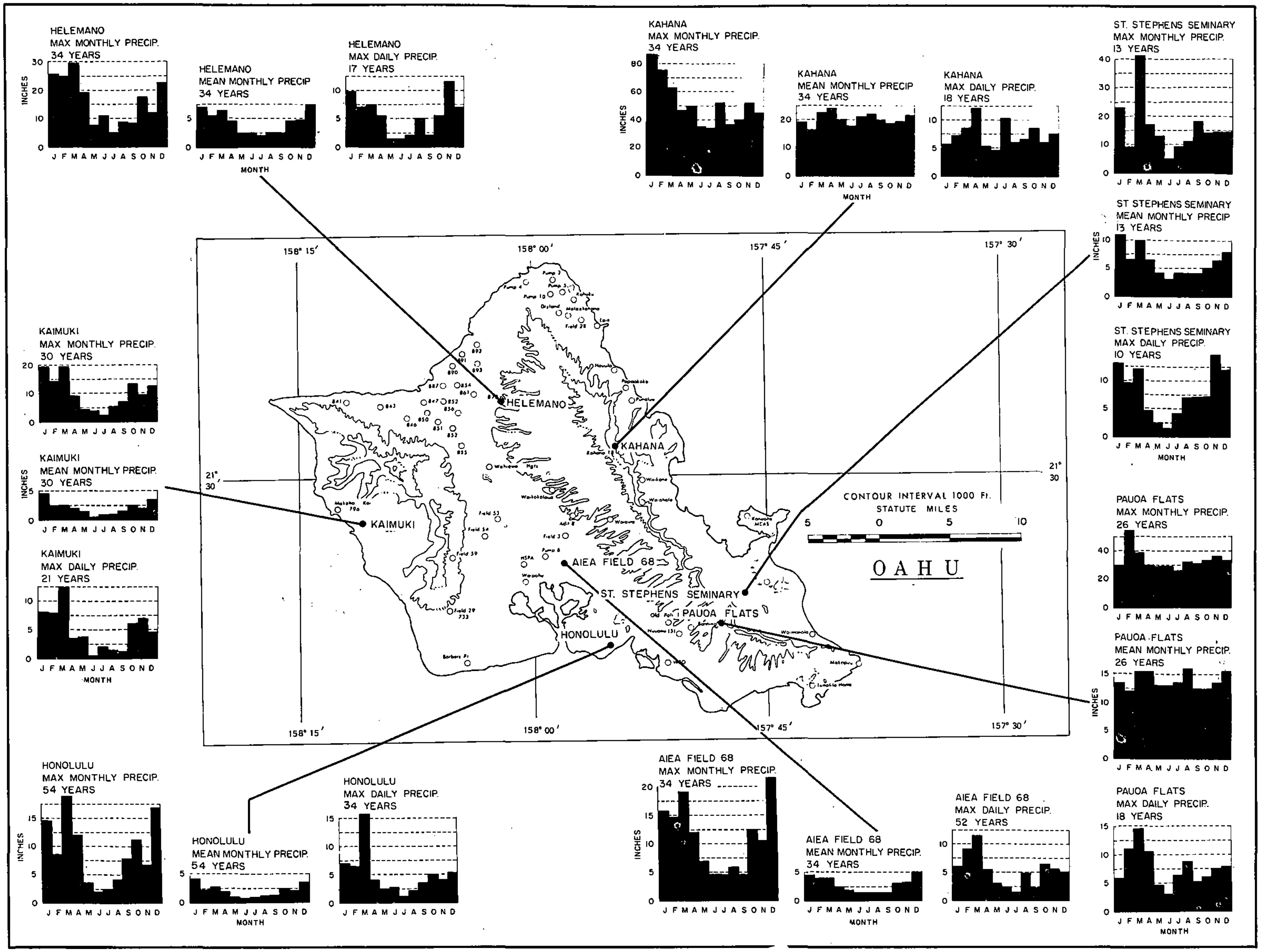


Fig. 3-12. RAINFALL REGIMES FOR SELECTED STATIONS - OAHU

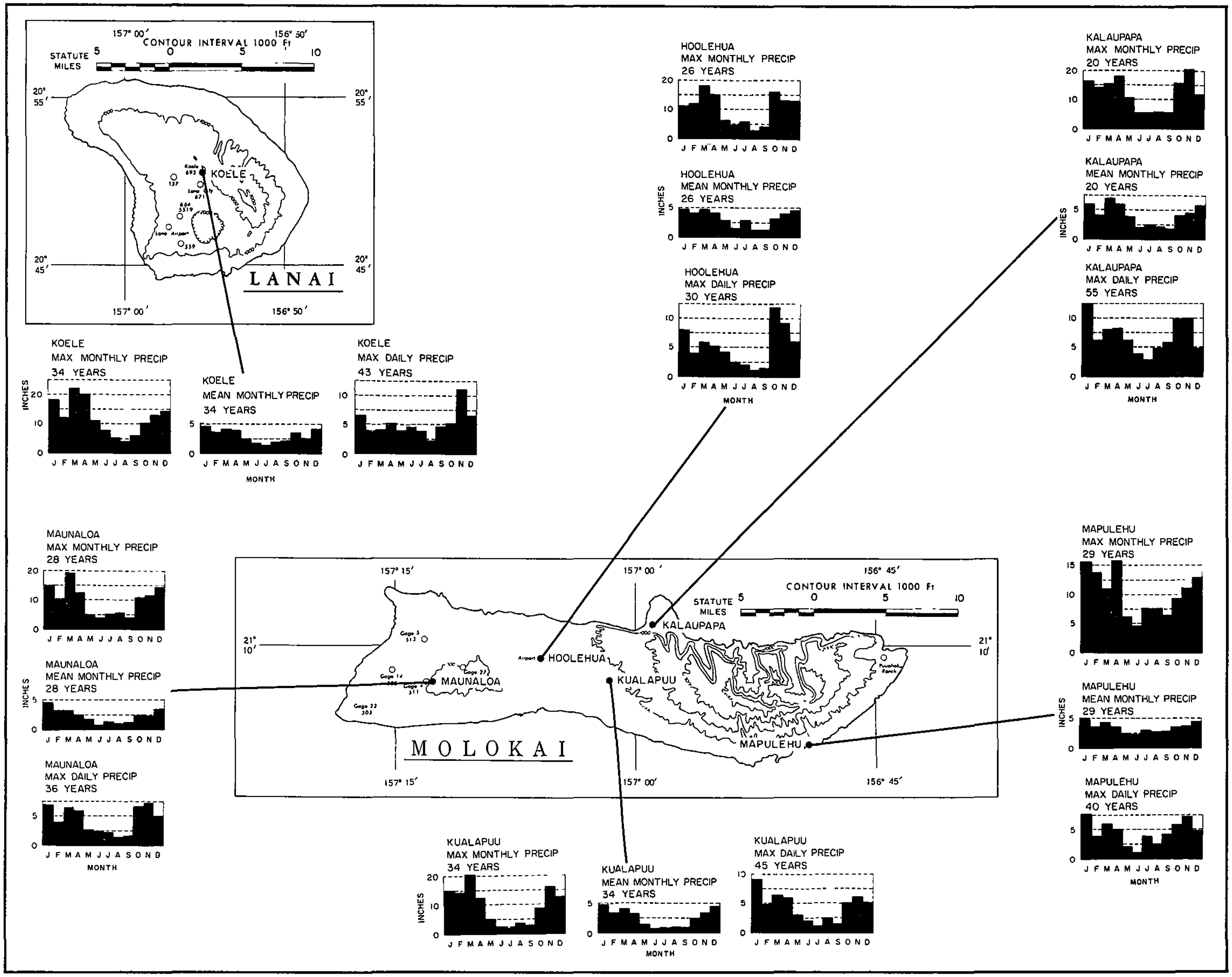


Fig. 3-13. RAINFALL REGIMES FOR SELECTED STATIONS - MOLOKAI AND LANAI

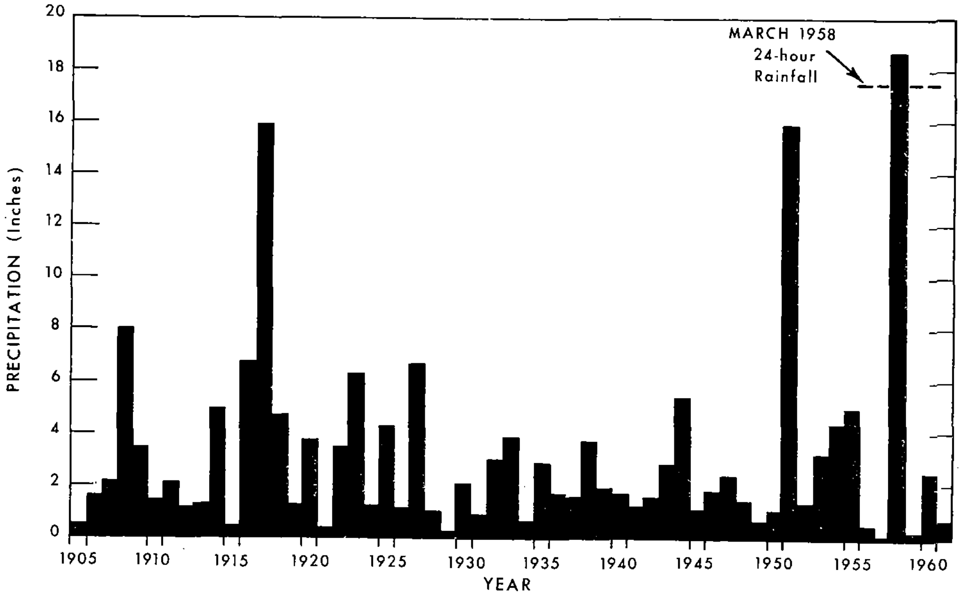
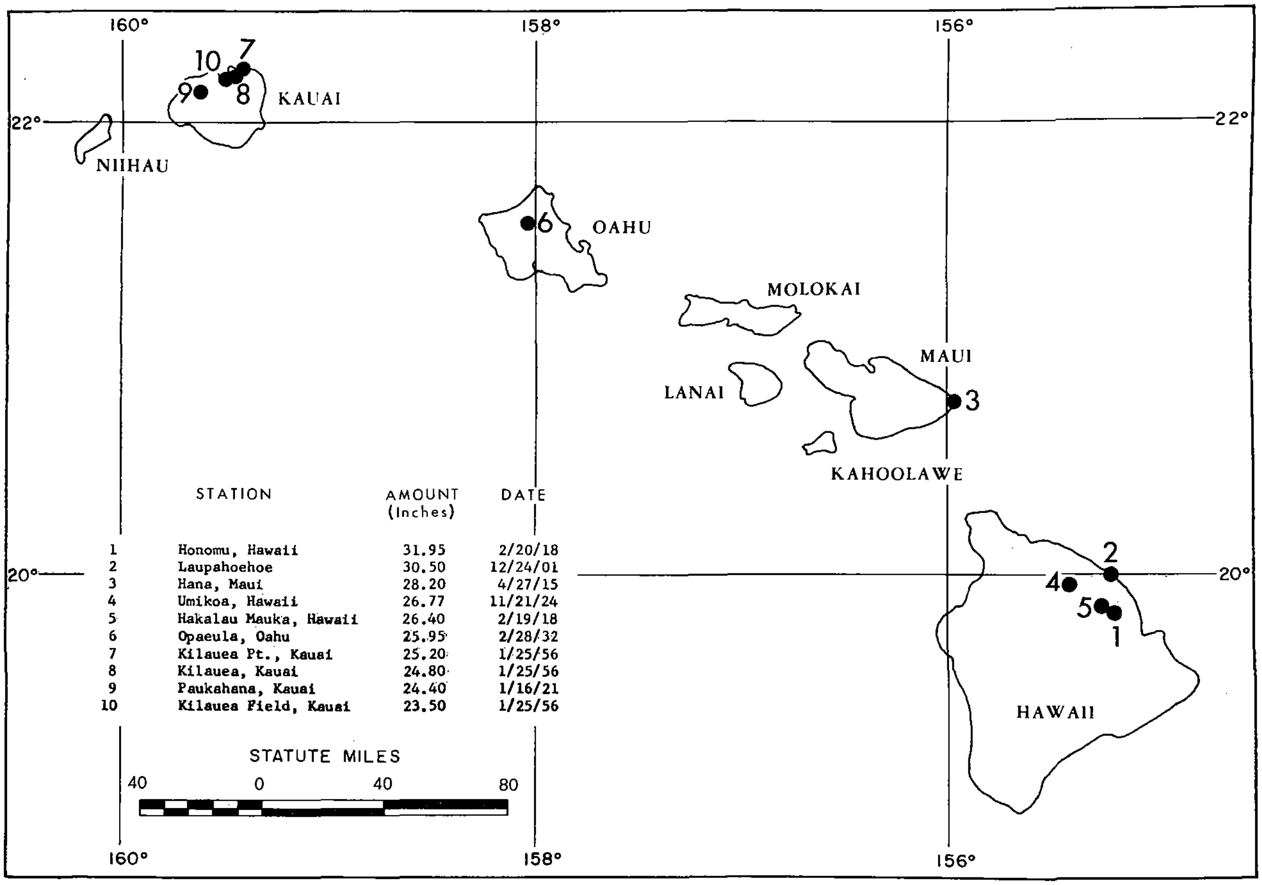


Fig. 3-14. MARCH PRECIPITATION AT HONOLULU



	STATION	AMOUNT (Inches)	DATE
1	Honomu, Hawaii	31.95	2/20/18
2	Laupahoehoe	30.50	12/24/01
3	Hana, Maui	28.20	4/27/15
4	Umikoa, Hawaii	26.77	11/21/24
5	Hakalau Mauka, Hawaii	26.40	2/19/18
6	Opaeula, Oahu	25.95	2/28/32
7	Kilauea Pt., Kauai	25.20	1/25/56
8	Kilauea, Kauai	24.80	1/25/56
9	Paukahana, Kauai	24.40	1/16/21
10	Kilauea Field, Kauai	23.50	1/25/56

Fig. 3-15. TEN GREATEST DAILY RAINS OF RECORD FOR THE HAWAIIAN ISLANDS

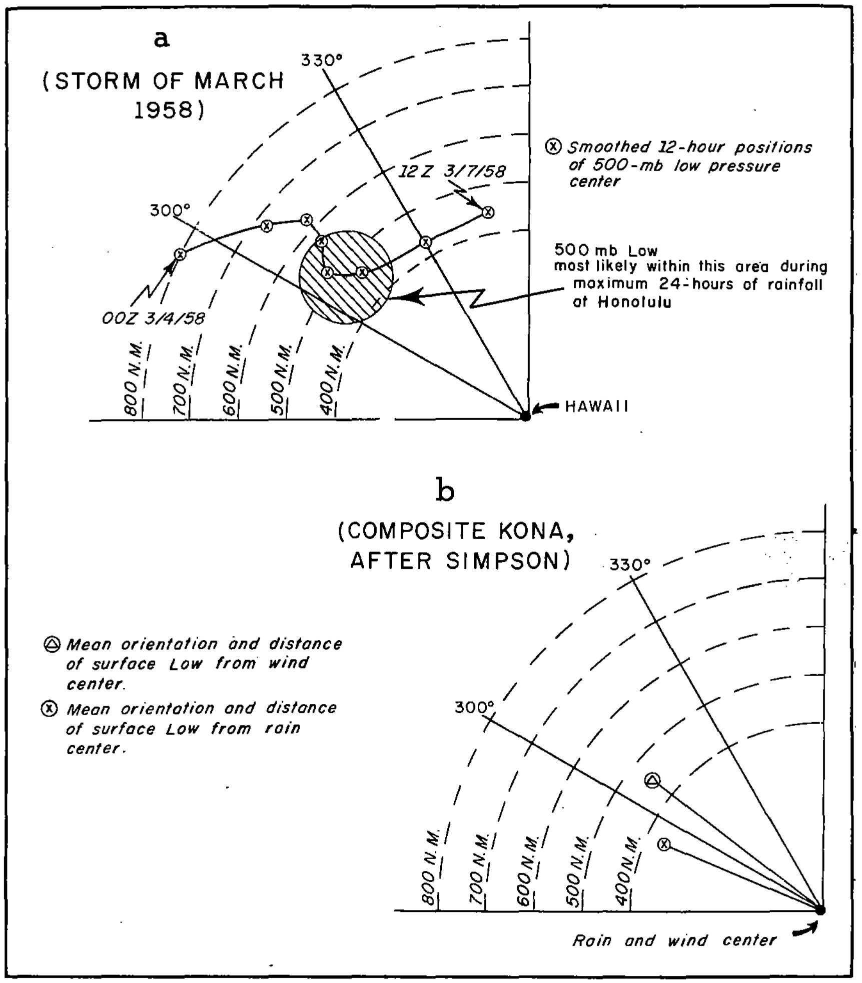


Fig. 4-1. COMPARISON OF MARCH 1958 STORM WITH COMPOSITE KONA SYNOPTIC DATA

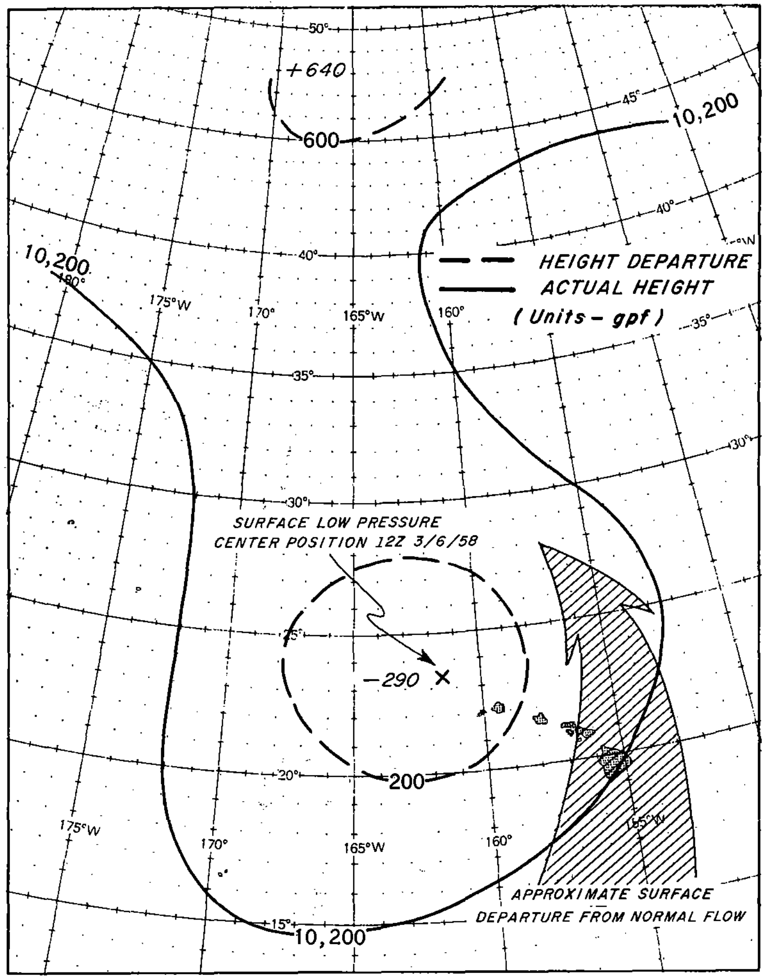


Fig. 4-2. SCHEMATIC OF MEAN 700-MB CONDITIONS FOR MARCH 4-8, 1958

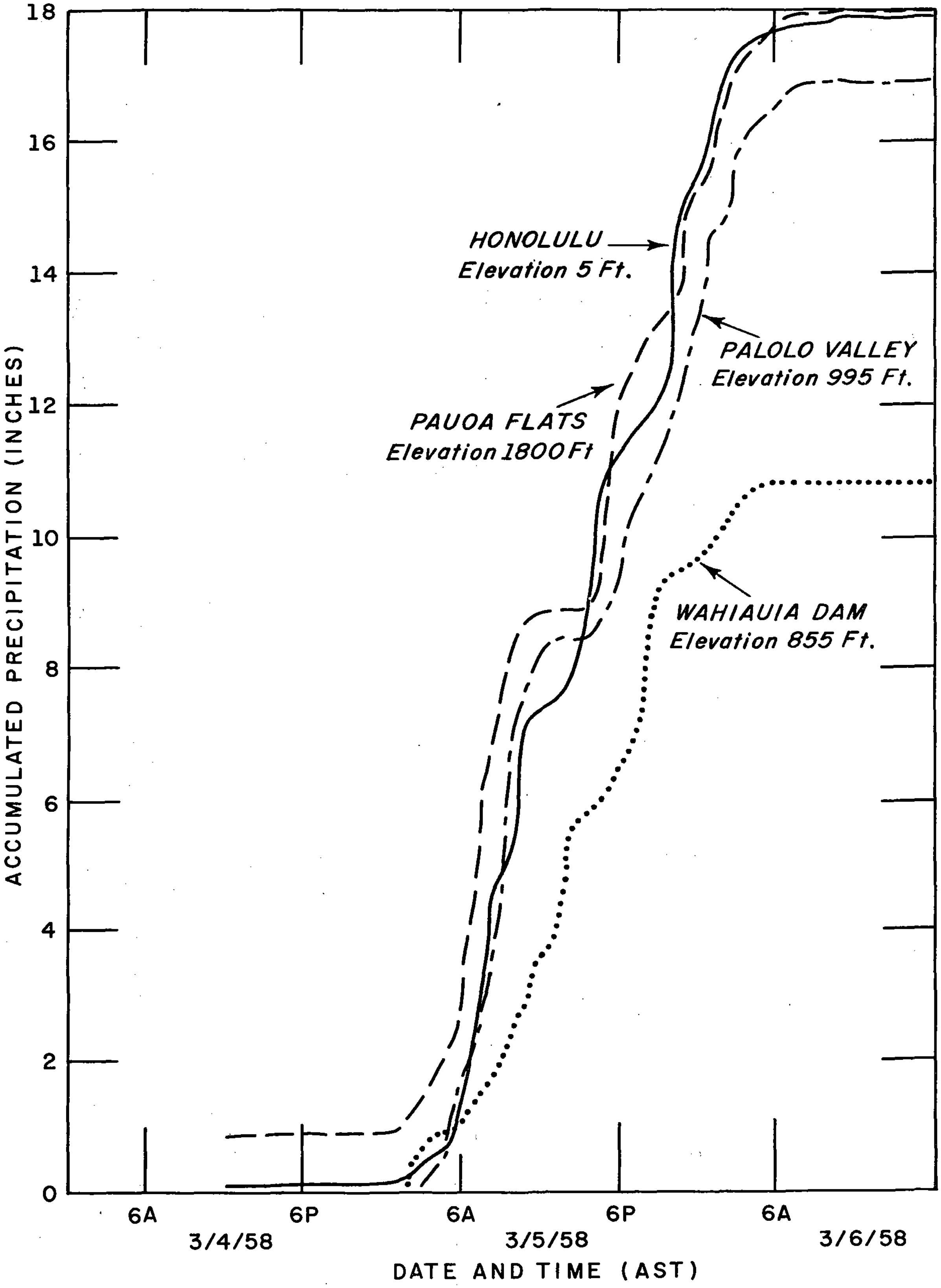


Fig. 4-3. MASS CURVES OF RAINFALL - MARCH 4-6, 1958

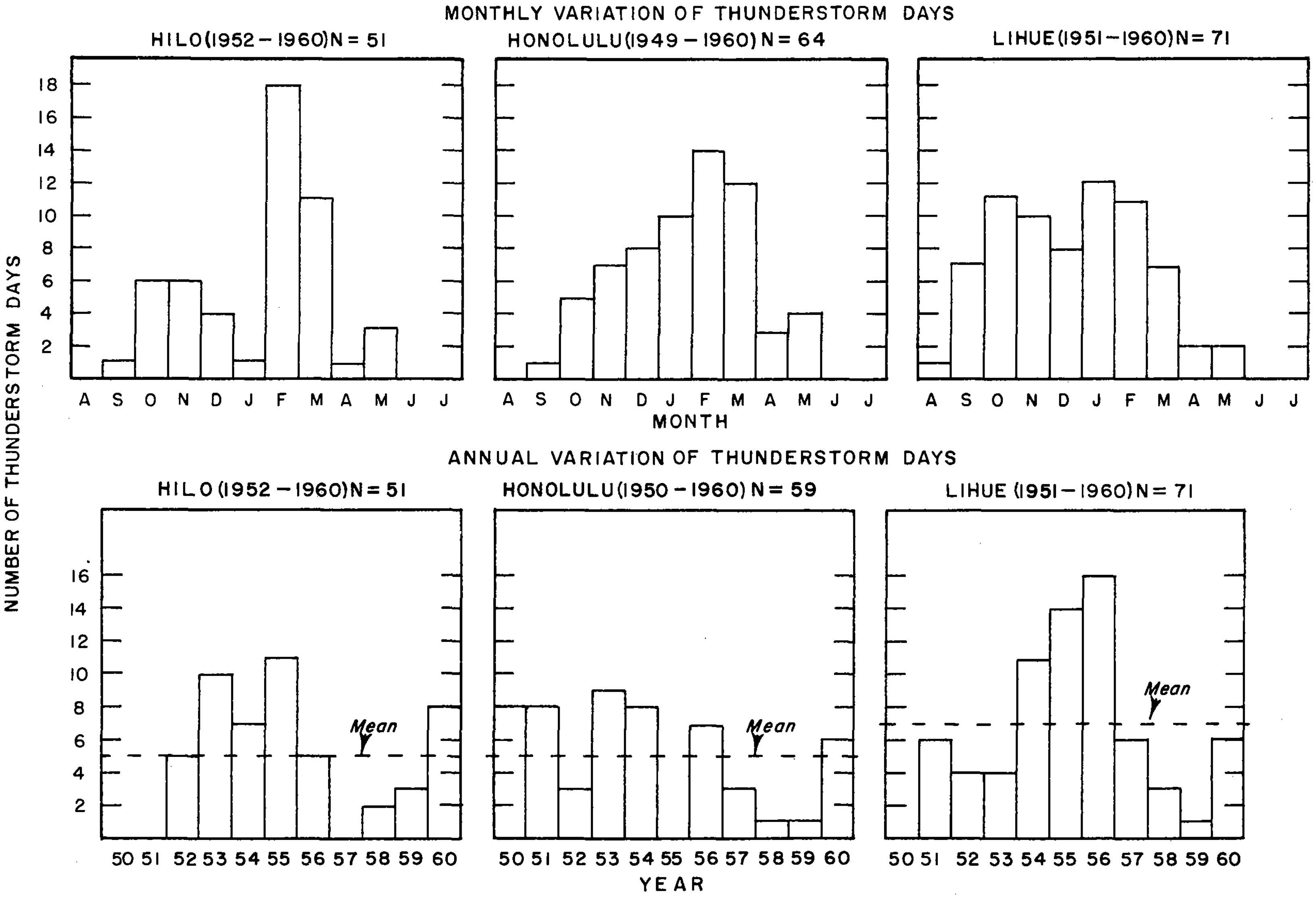


Fig. 4-4. VARIATION OF THUNDERSTORM DAYS BY MONTH AND YEAR

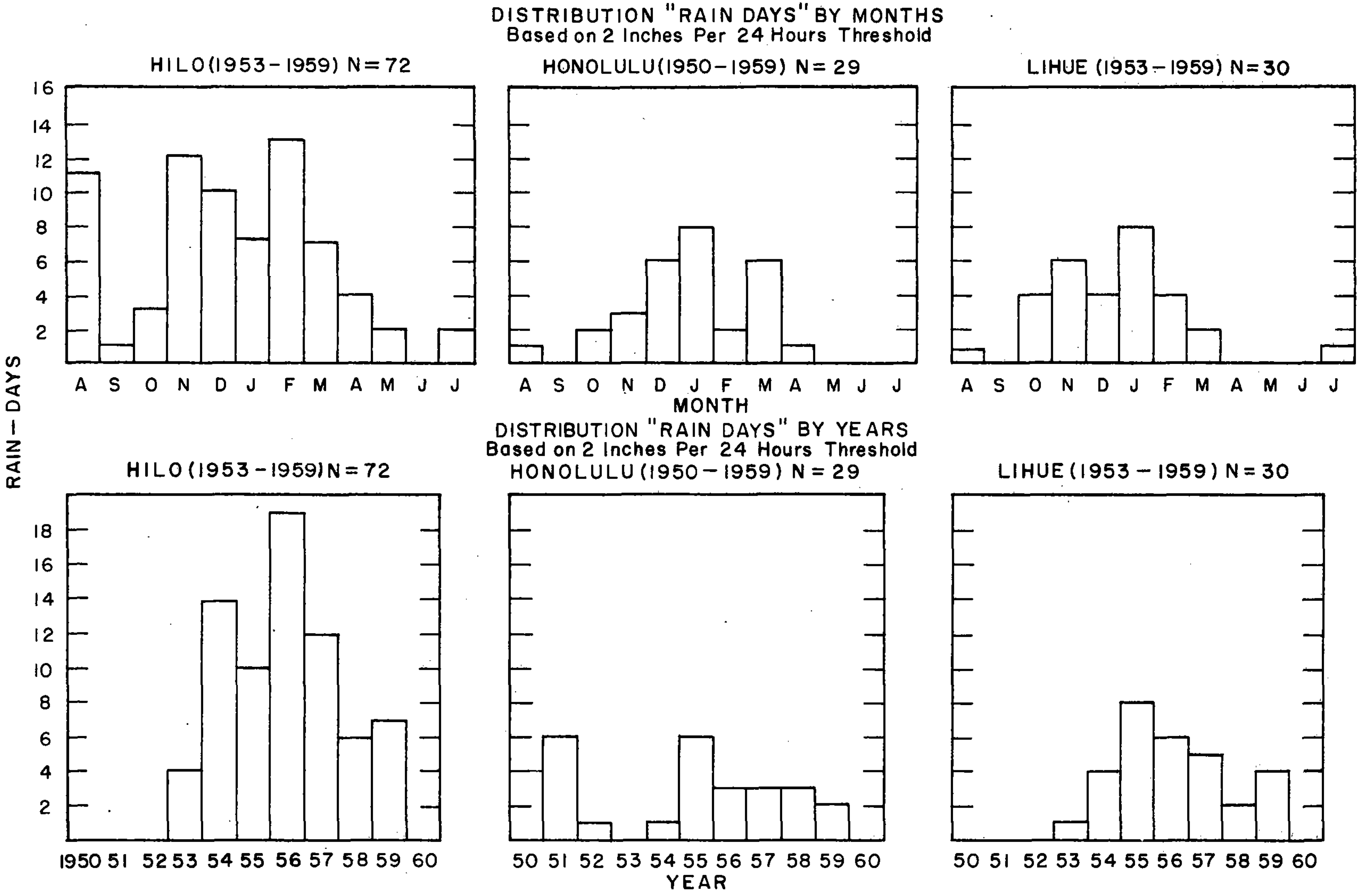


Fig. 4-5. DISTRIBUTION OF RAIN DAYS BY MONTH AND YEAR

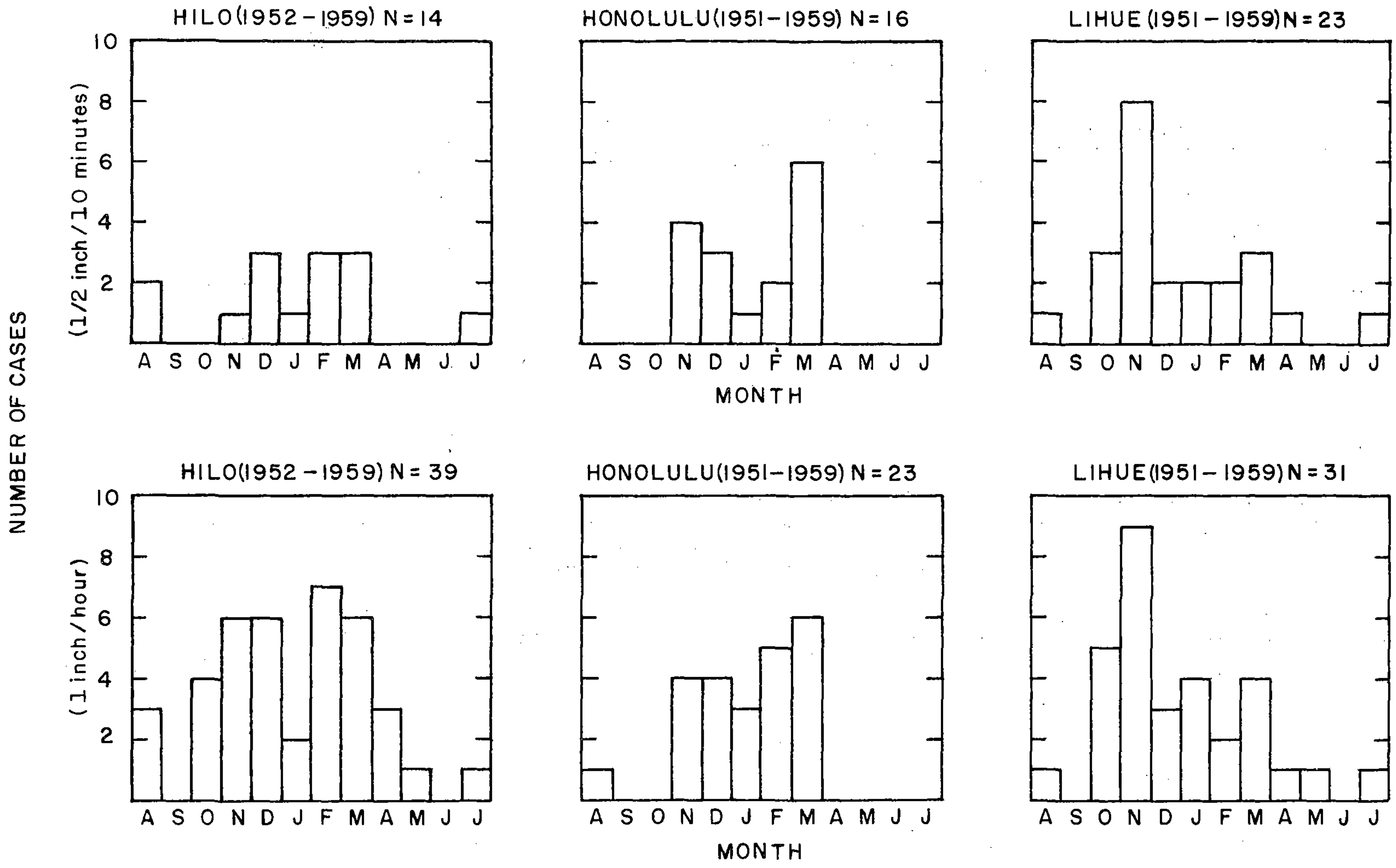
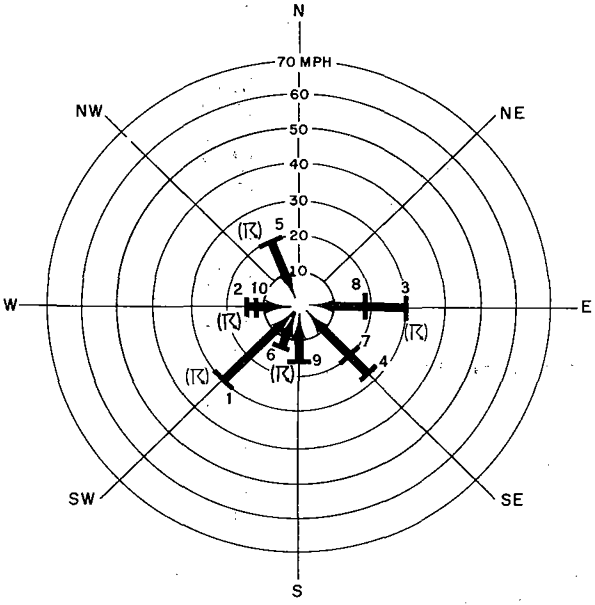
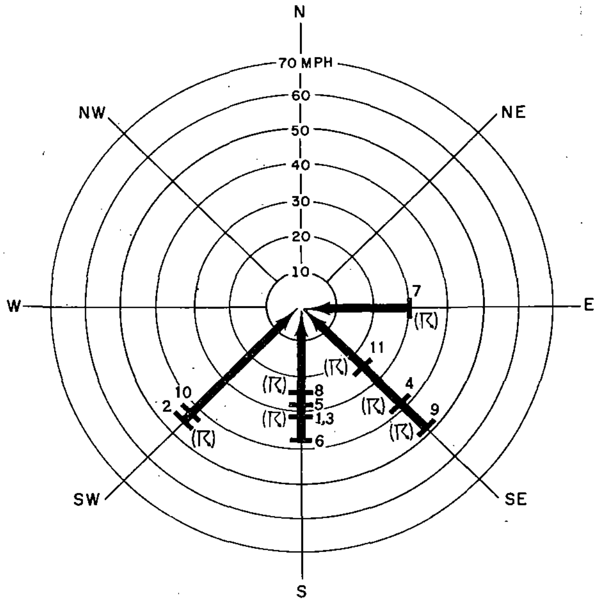


Fig. 4-6. **SEASONAL DISTRIBUTION OF SHORT-DURATION RAINS**



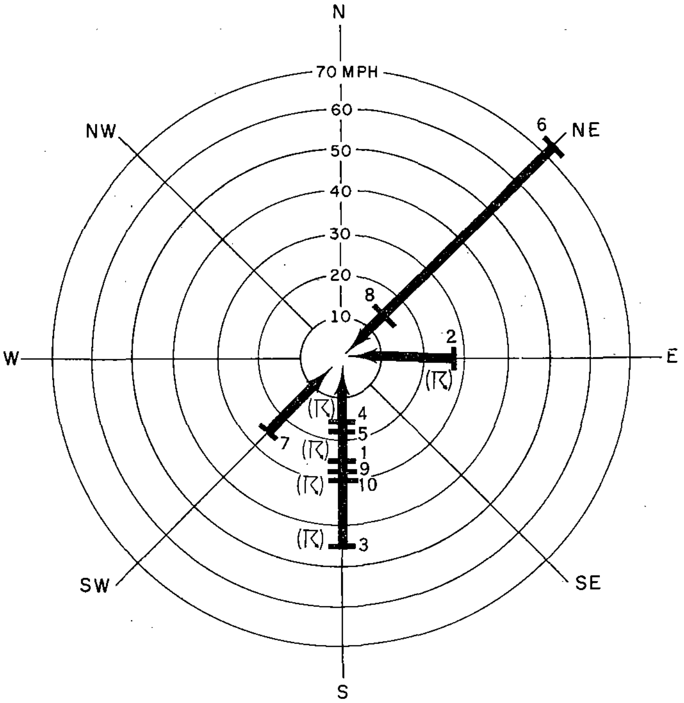
NUMBERS INDICATE RANK OF 24-HOUR RAINFALL
(⛈) *INDICATES THUNDER REPORTED DURING RAINFALL*

Fig. 4-7. WINDS AND THUNDERSTORMS WITH MAXIMUM 24-HOUR RAIN - HILO



NUMBERS INDICATE RANK OF 24-HOUR RAINFALL
(⛈) *INDICATES THUNDER REPORTED DURING RAINFALL*

Fig. 4-8. WINDS AND THUNDERSTORMS WITH MAXIMUM 24-HOUR RAIN - HONOLULU



NUMBERS INDICATE RANK OF 24-HOUR RAINFALL
(⛈) *INDICATES THUNDER REPORTED DURING RAINFALL*

Fig. 4-9. WINDS AND THUNDERSTORMS WITH MAXIMUM 24-HOUR RAIN - LIHUE

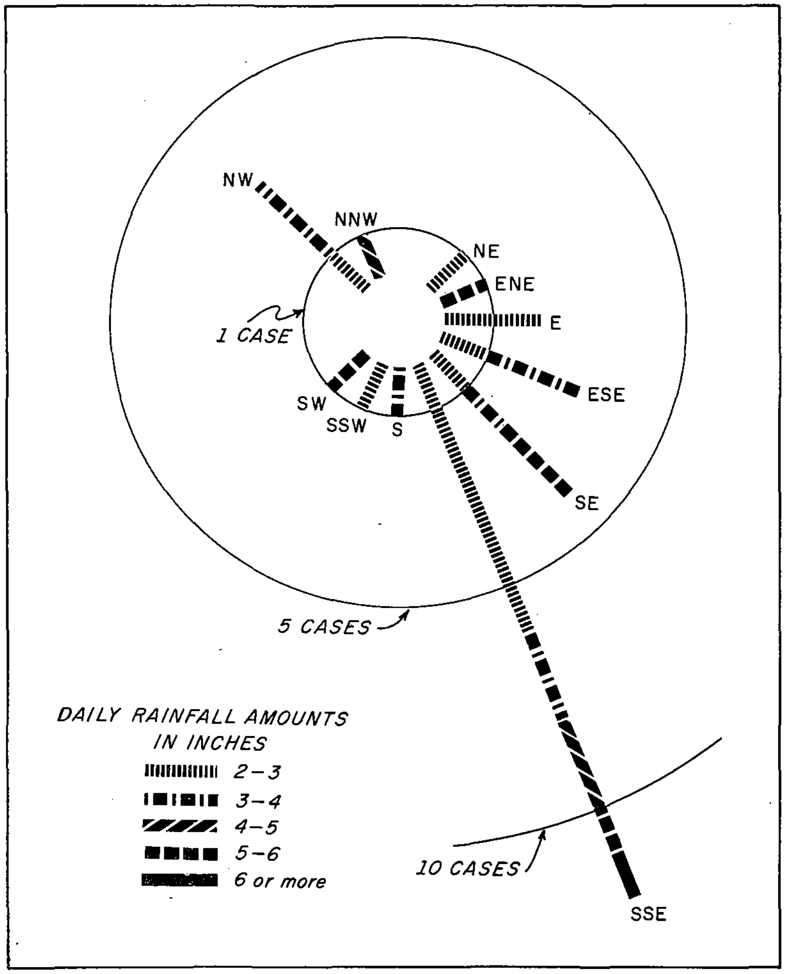


Fig. 4-10. PREVAILING WIND DIRECTION ON DAYS WITH TWO OR MORE INCHES OF PRECIPITATION - HONOLULU

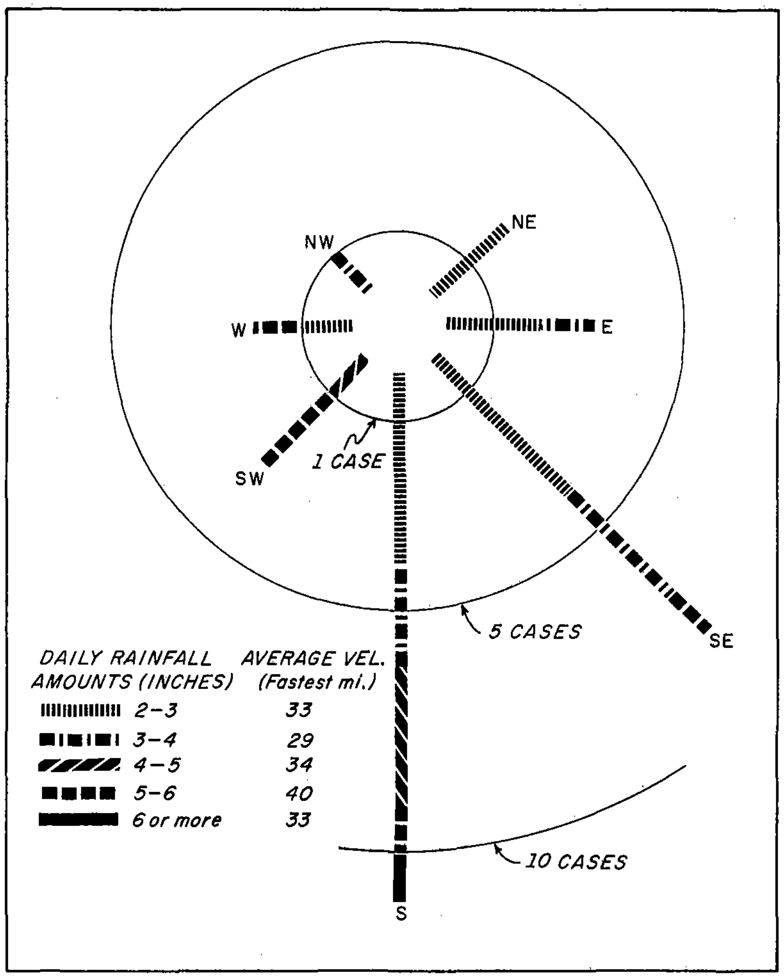


Fig. 4-11. FASTEST MILE OF WIND ON DAYS WITH TWO OR MORE INCHES OF PRECIPITATION - HONOLULU

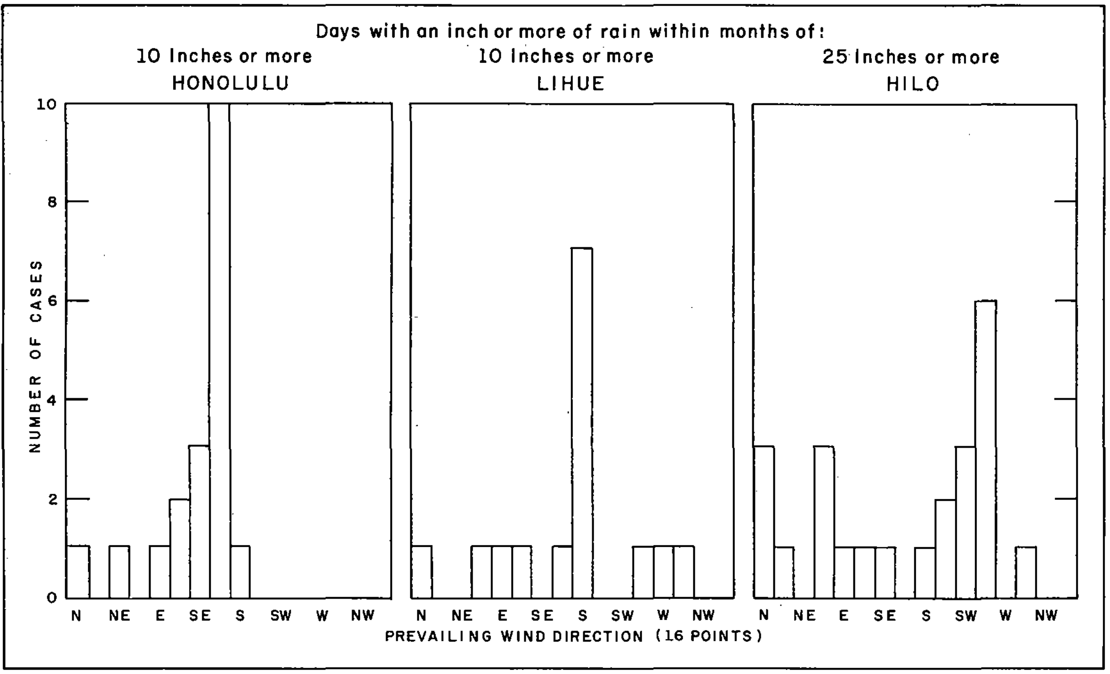


Fig. 4-12. SIGNIFICANT RAIN-BEARING WINDS WITHIN RAINY MONTHS

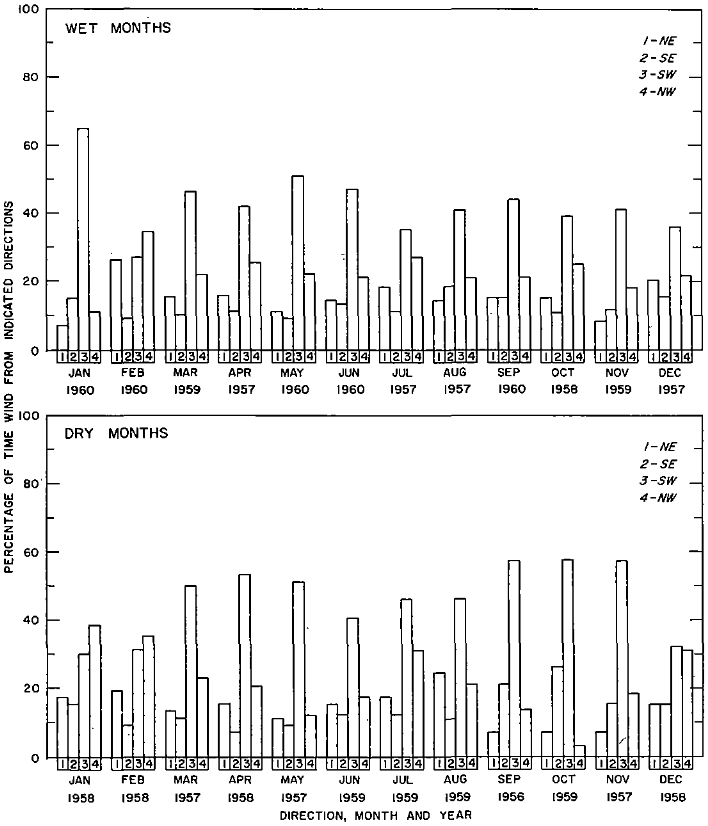


Fig. 4-13. WIND CONTRASTS FOR WET AND DRY MONTHS - HILO

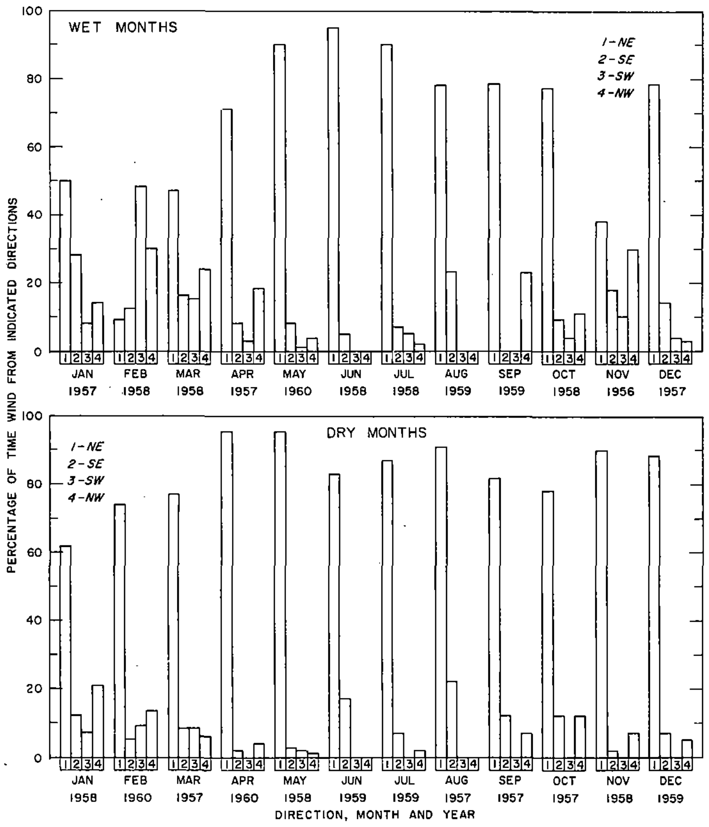


Fig. 4-14. **WIND CONTRASTS FOR WET AND DRY MONTHS - HONOLULU**

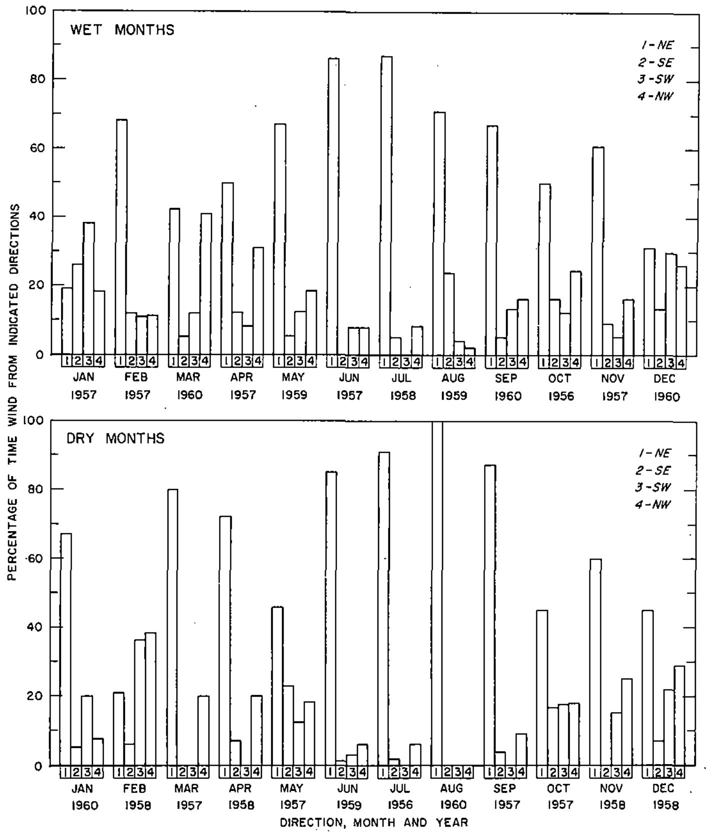


Fig. 4-15. **WIND CONTRASTS FOR WET AND DRY MONTHS - LIHUE**

Point No.	Dur. (hrs)	P/M Ratio	Station	Date	Rain (in)
1	1/3	0.6	Pupukea, Hawaii	9/19/07	1.37
2	1/2	2.9	Kilauea Plantation, Kauai	1/25/56	6.0
3	3/4	2.0	Puuwaawaa, Hawaii	9/23/07	4.0
4	3/4	3.2	Paauhau, Hawaii	4/2/61	6.0
5	3	6.7	Moanalua Valley, Oahu	11/18/30	15.2
6	5	8.6	Paauhau, Hawaii	4/2-3/61	16.0
7	6	8.2	Keanae Valley, Maui	12/22/06	12.5
8	12	11.8	Paauhau, Hawaii	4/2-3/61	22.0
9	13-1/2	9.65	Kilauea Plantation, Kauai	11/11-12/55	19.85
10	Day	16.7	Hana, Maui	4/27/15	28.20
11	Day	15.9	Umikoa, Hawaii	11/21/24	26.77
12	Day	15.1	Papaikou, Hawaii	4/27/15	23.00
13	Day	13.8	Honomanu Valley, Maui	3/11/09	21.02
14	Day	13.7	Paukahana, Kauai	1/16/21	24.40

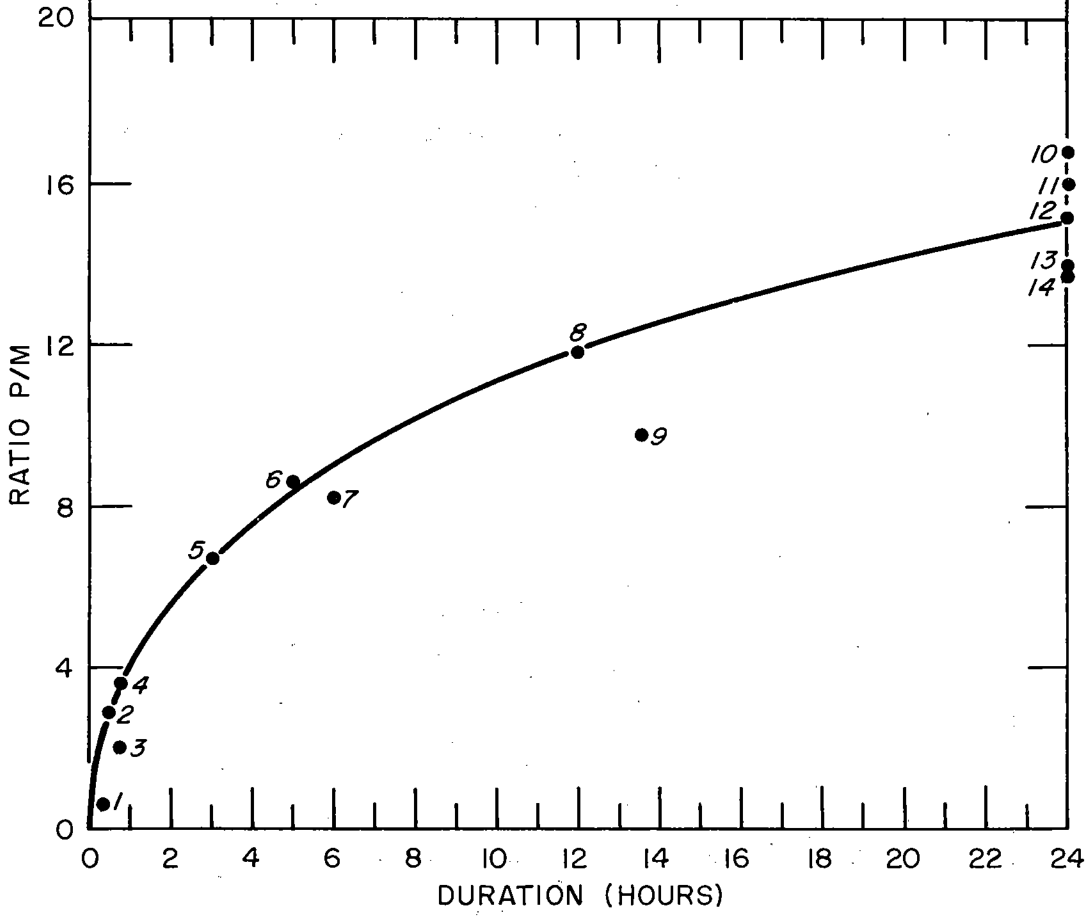


Fig. 5-1. **MAXIMUM P/M RATIOS**

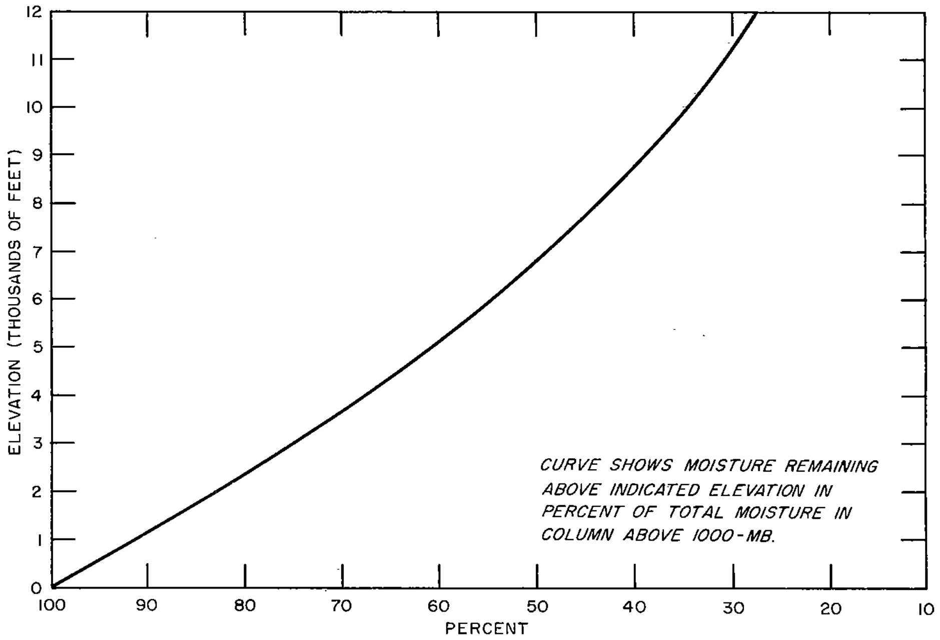


Fig. 5-2. MOISTURE DEPLETION FOR A SATURATED SOUNDING WITH A 73°F 1000-MB TEMPERATURE

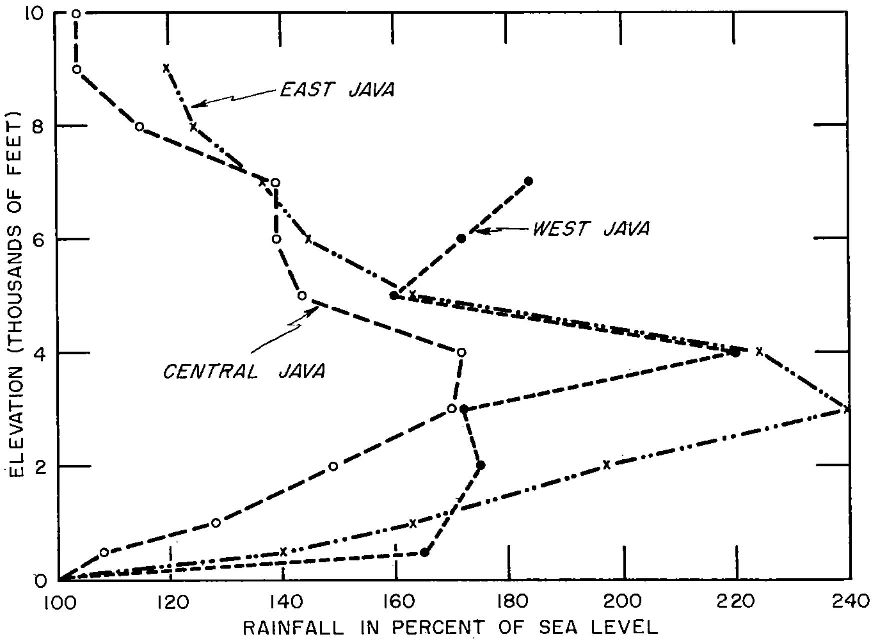


Fig. 5-3. MEAN ANNUAL RAINFALL VS. ELEVATION - JAVA, INDONESIA

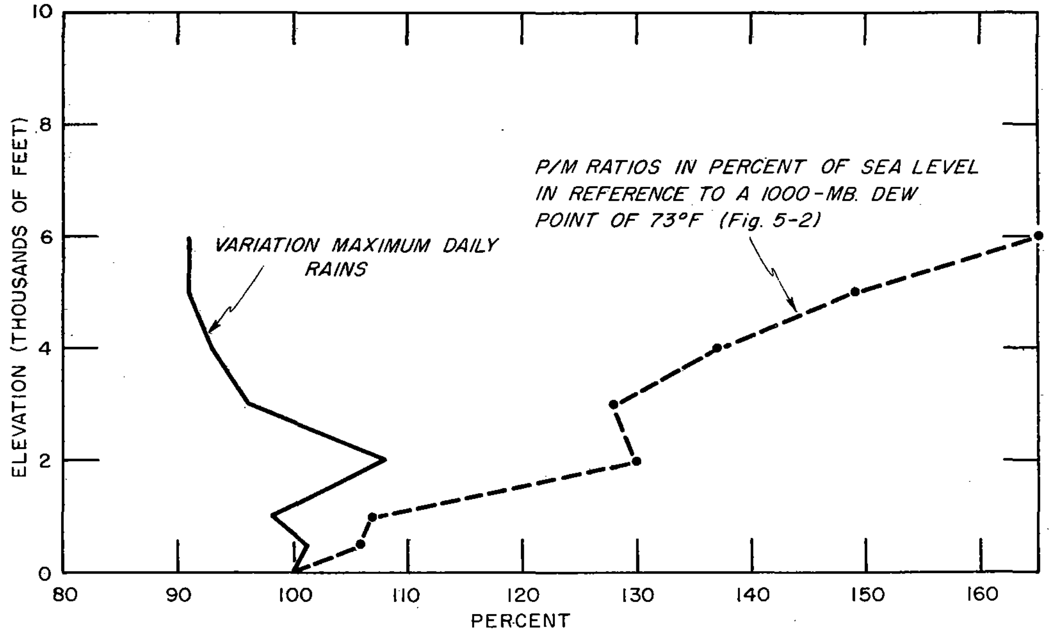


Fig. 5-4. VARIATION OF MAXIMUM DAILY RAINS OF RECORD IN PERCENT OF SEA LEVEL - JAVA, INDONESIA

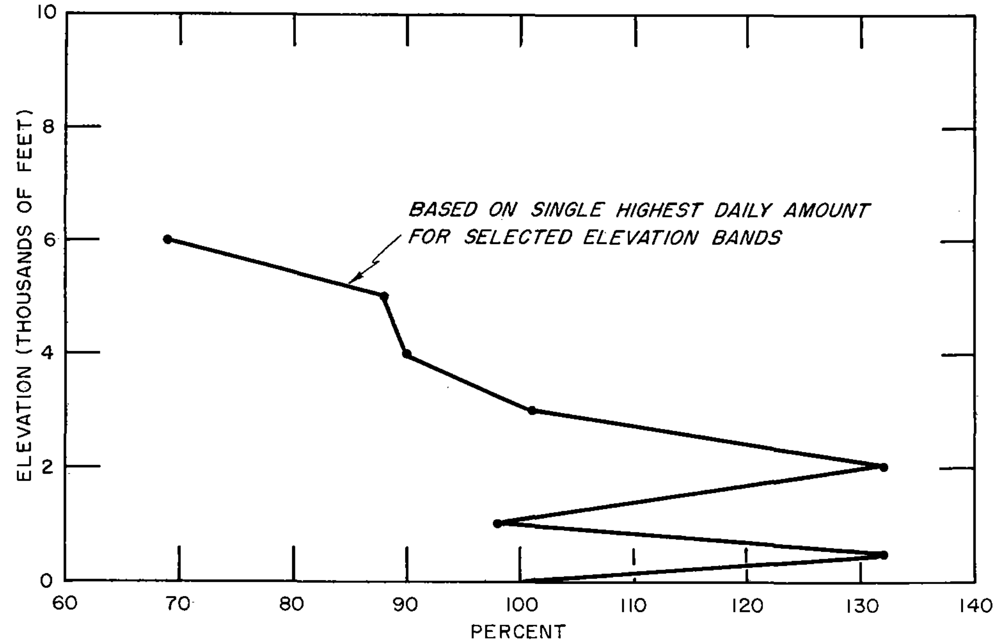
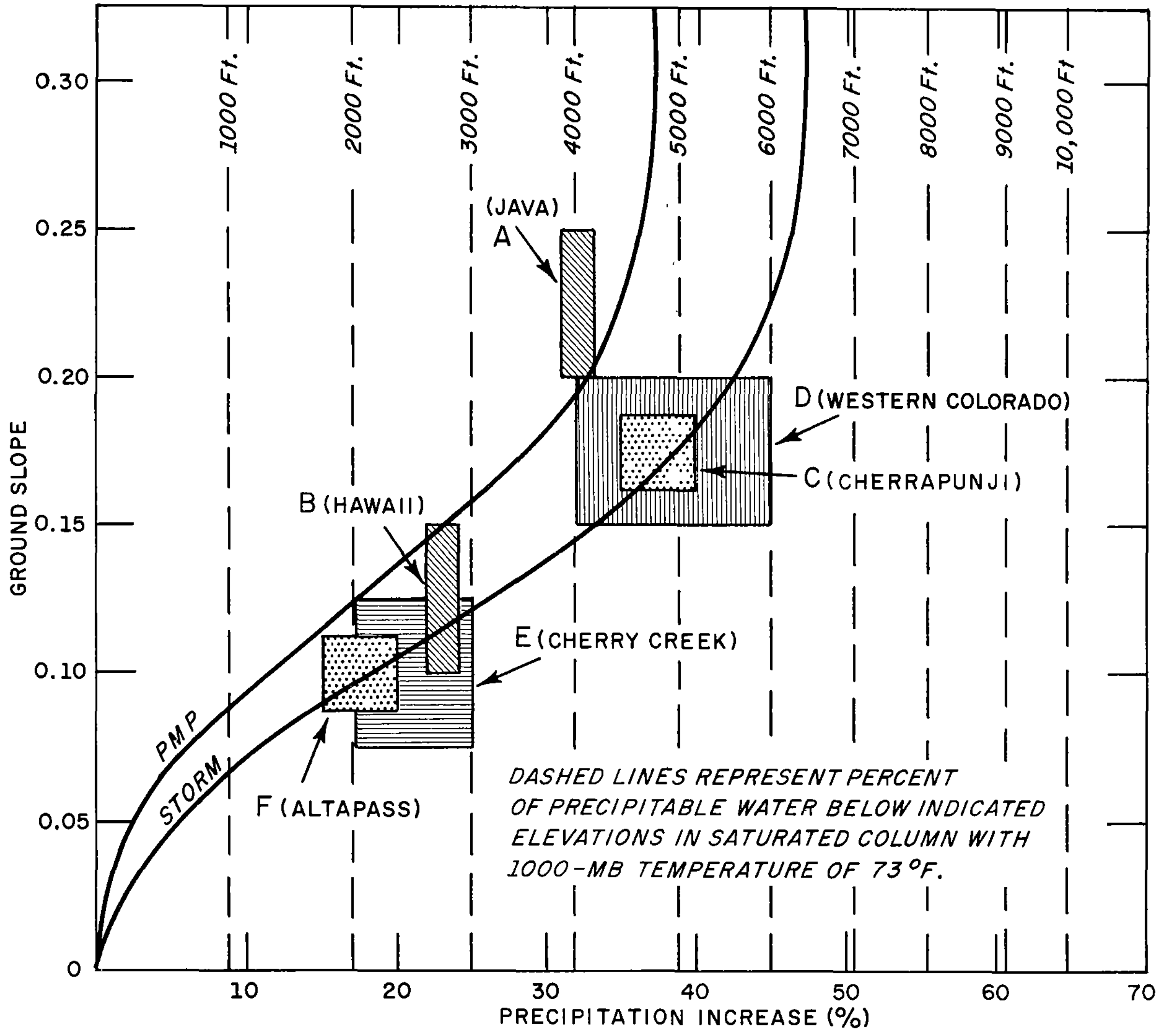


Fig. 5-5. VARIATION OF ABSOLUTE MAXIMUM DAILY RAINS OF RECORD IN PERCENT OF SEA LEVEL - JAVA, INDONESIA



DASHED LINES REPRESENT PERCENT OF PRECIPITABLE WATER BELOW INDICATED ELEVATIONS IN SATURATED COLUMN WITH 1000-MB TEMPERATURE OF 73°F.

Fig. 5-6. **RAIN INTENSIFICATION FOR GROUND SLOPE**

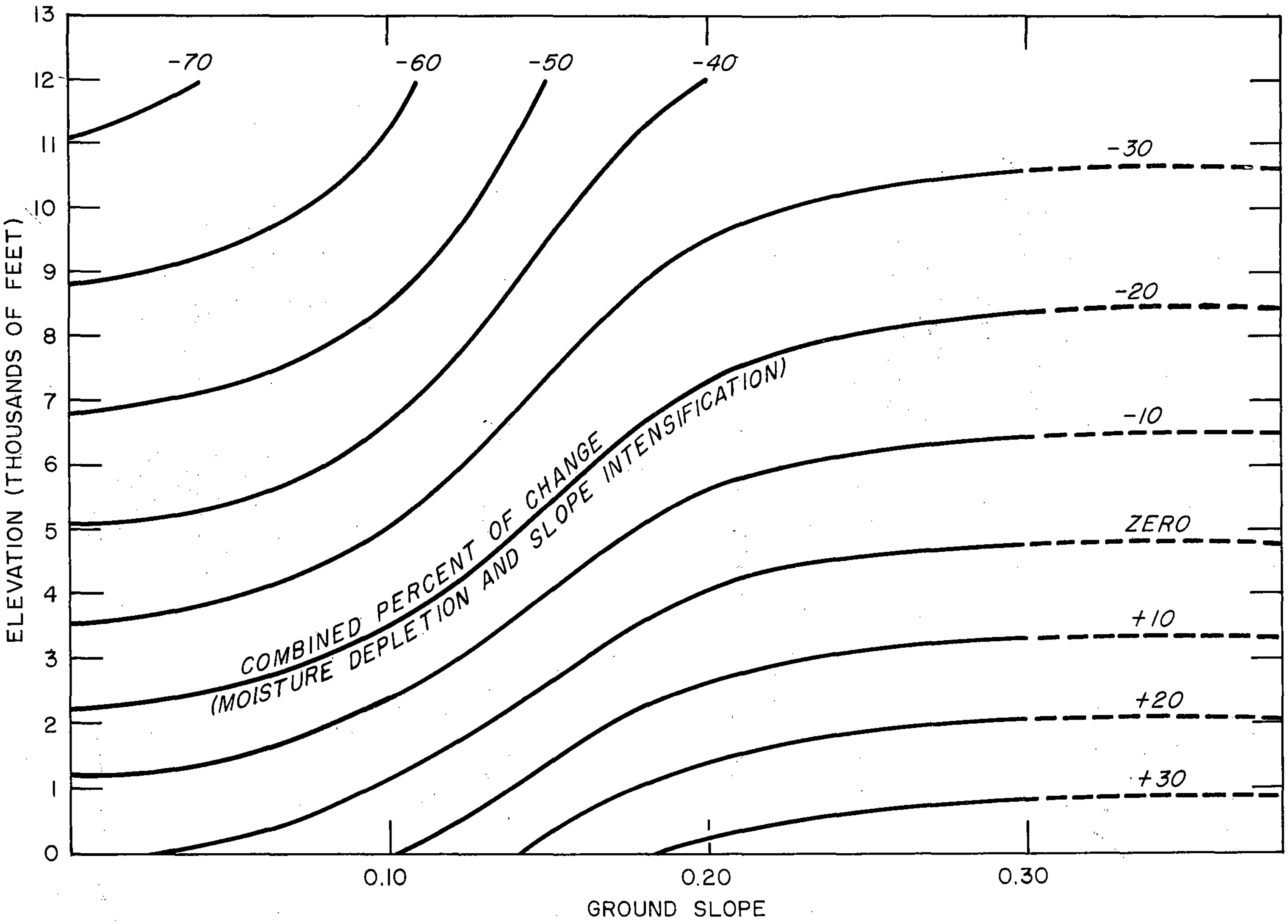


Fig. 5-7. RAINFALL ADJUSTMENT CURVES

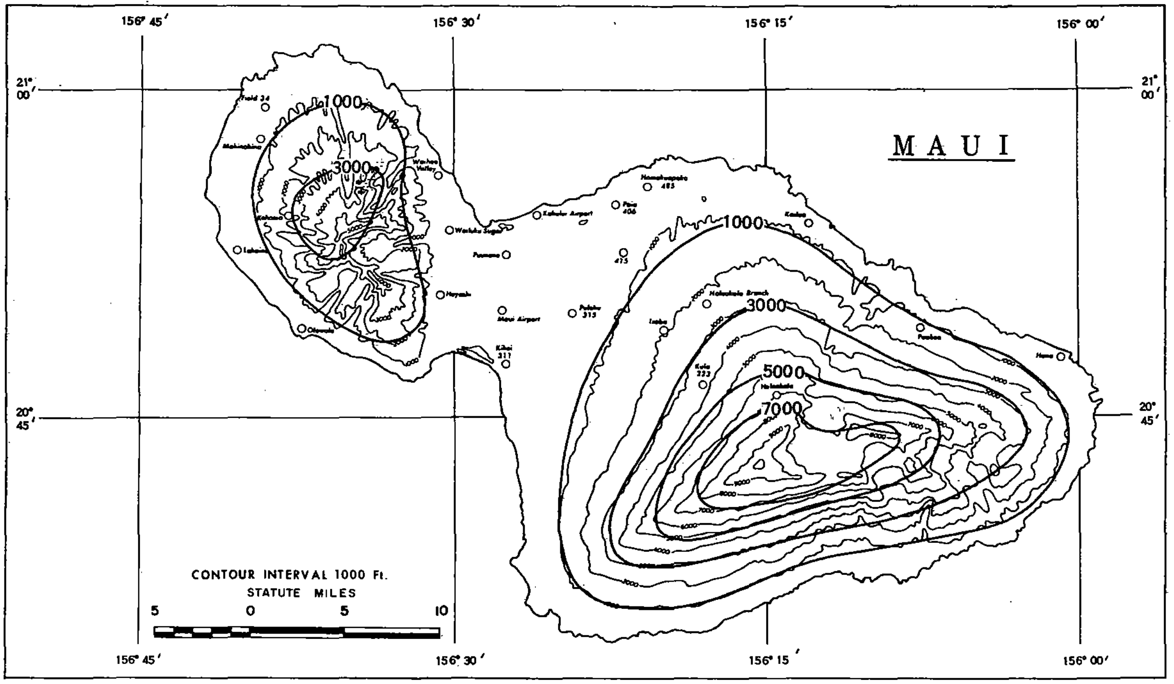


Fig. 5-8. EFFECTIVE BARRIER (FEET)

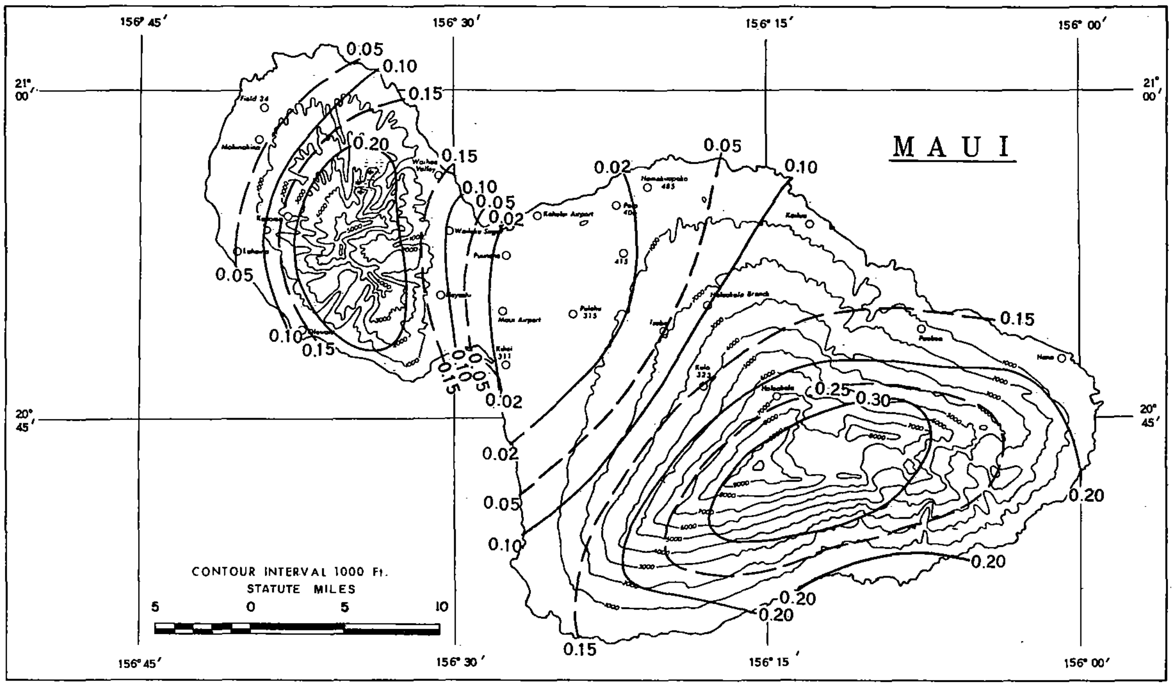


Fig. 5-9. EFFECTIVE GROUND SLOPE

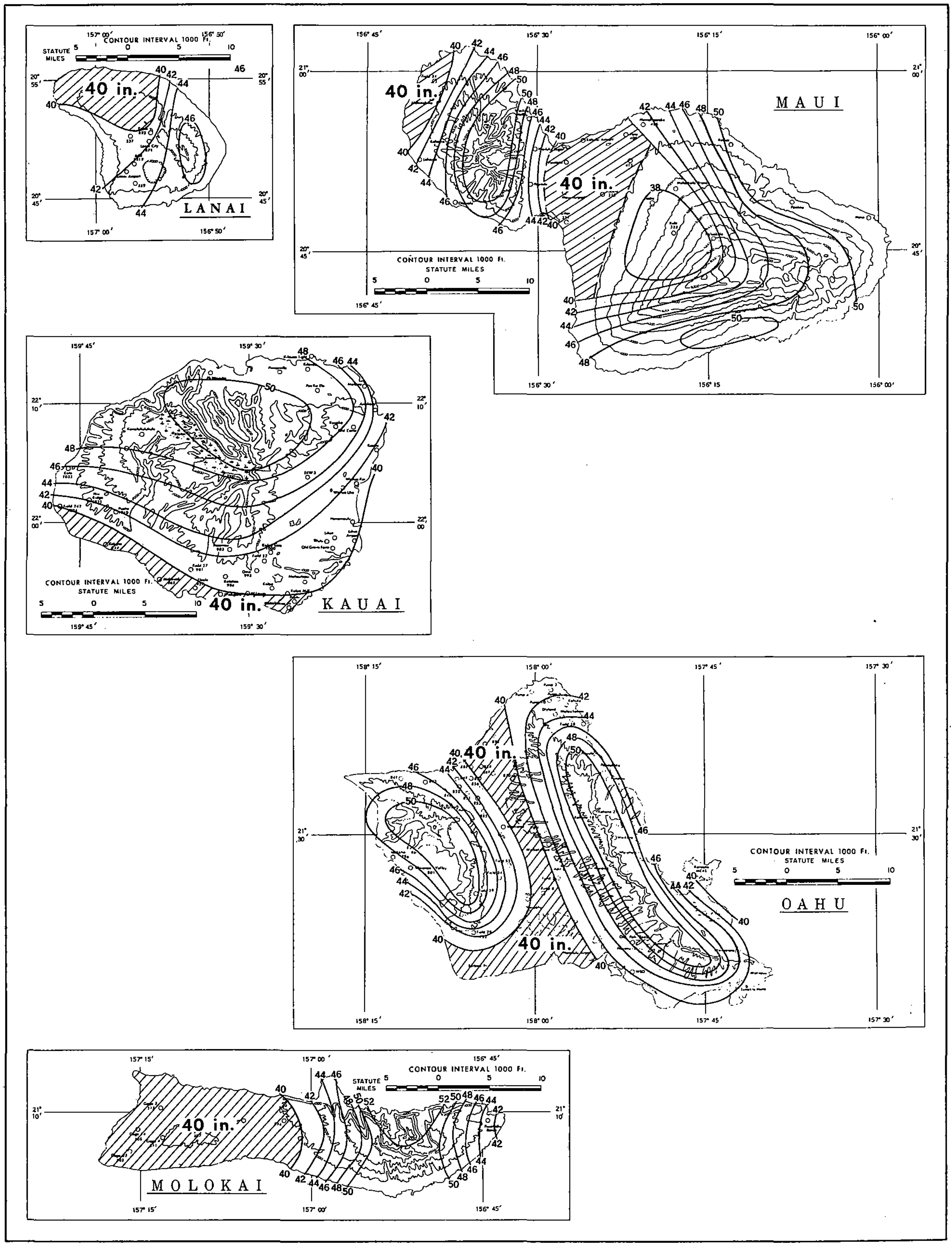


Fig. 5-10. 24-HOUR PMP - INCHES

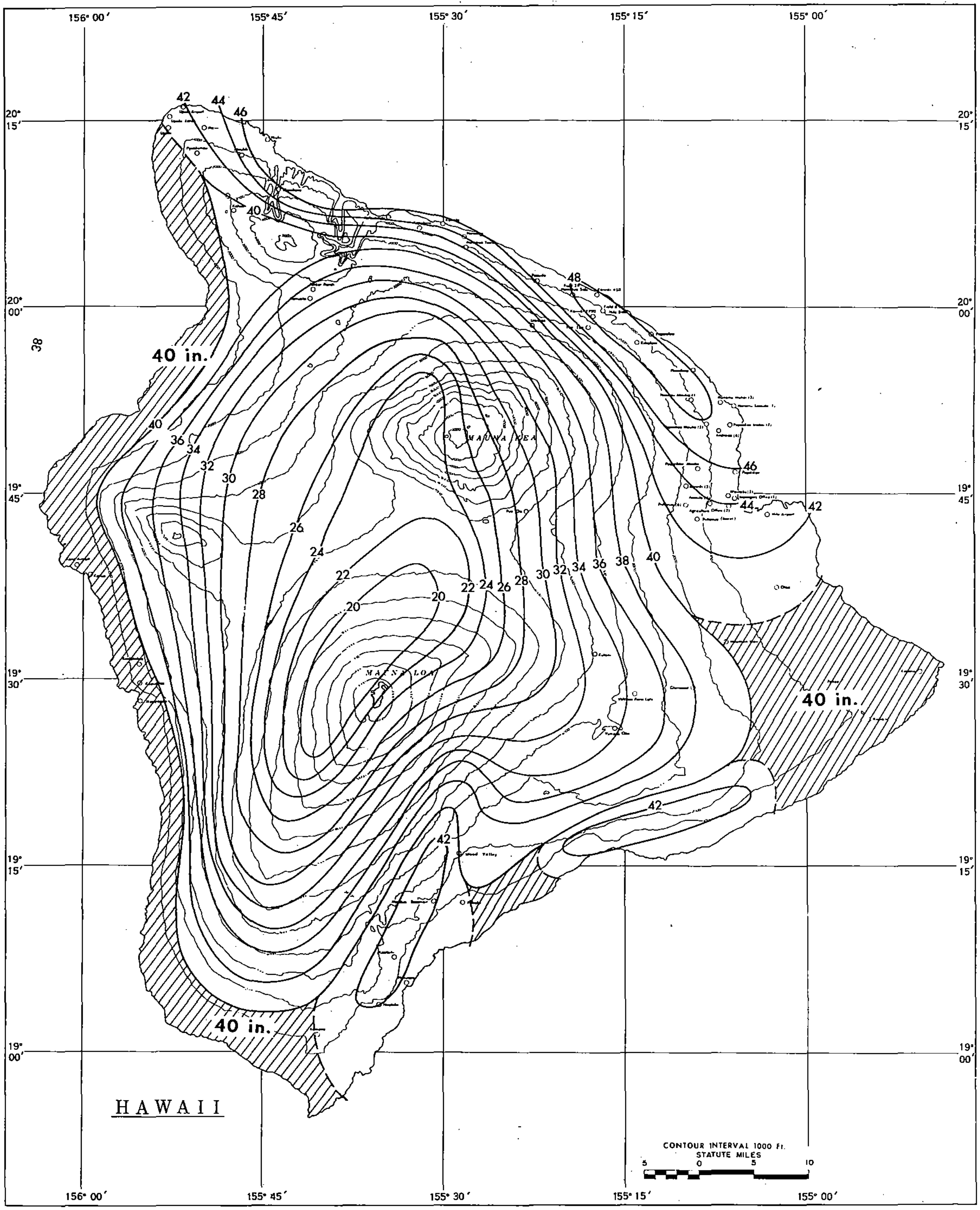


Fig. 5-11. 24-HOUR PMP - INCHES (HAWAII)

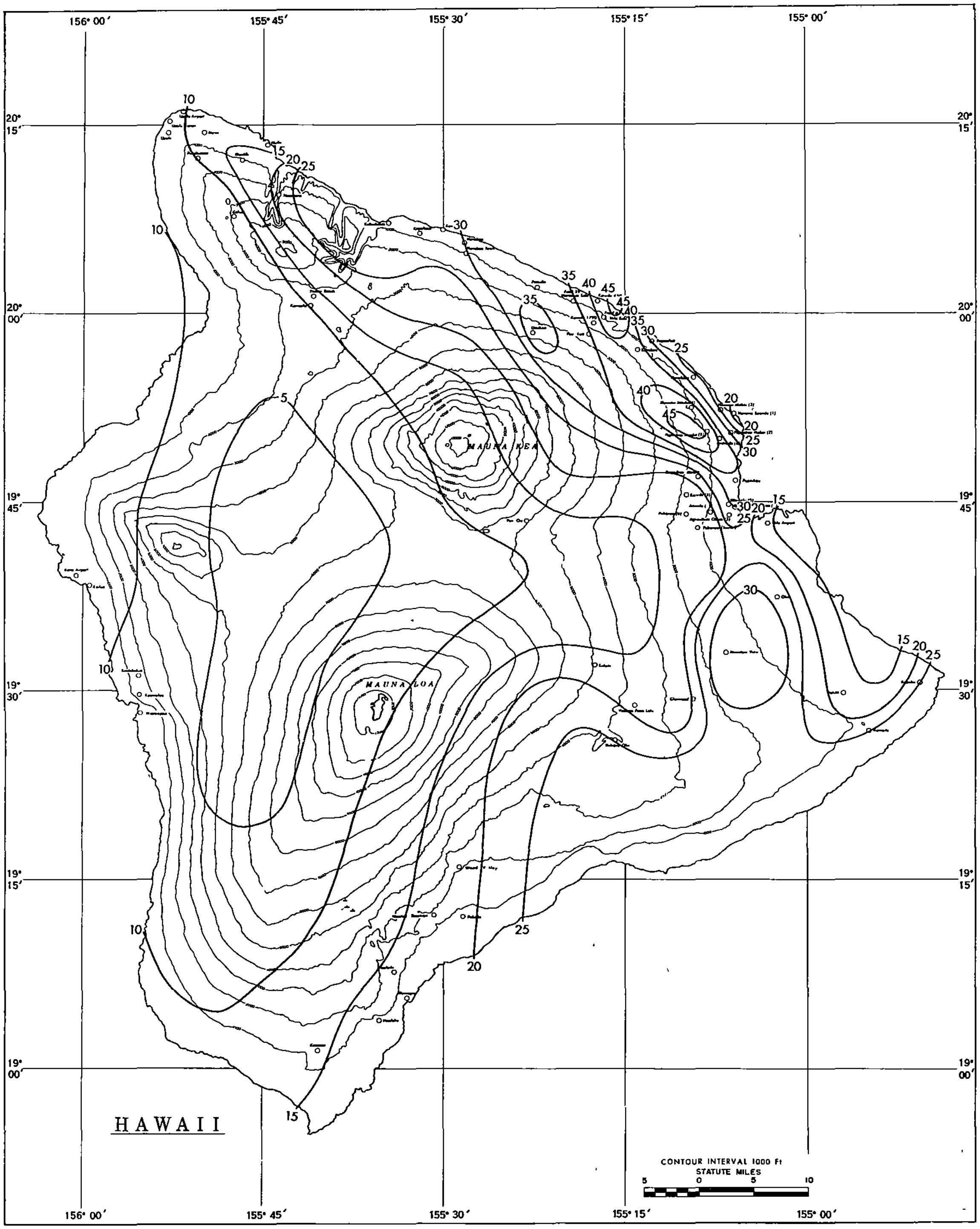


Fig. 5-12. MOISTURE ADJUSTED MAXIMIZED OBSERVED DAILY RAINFALL - INCHES

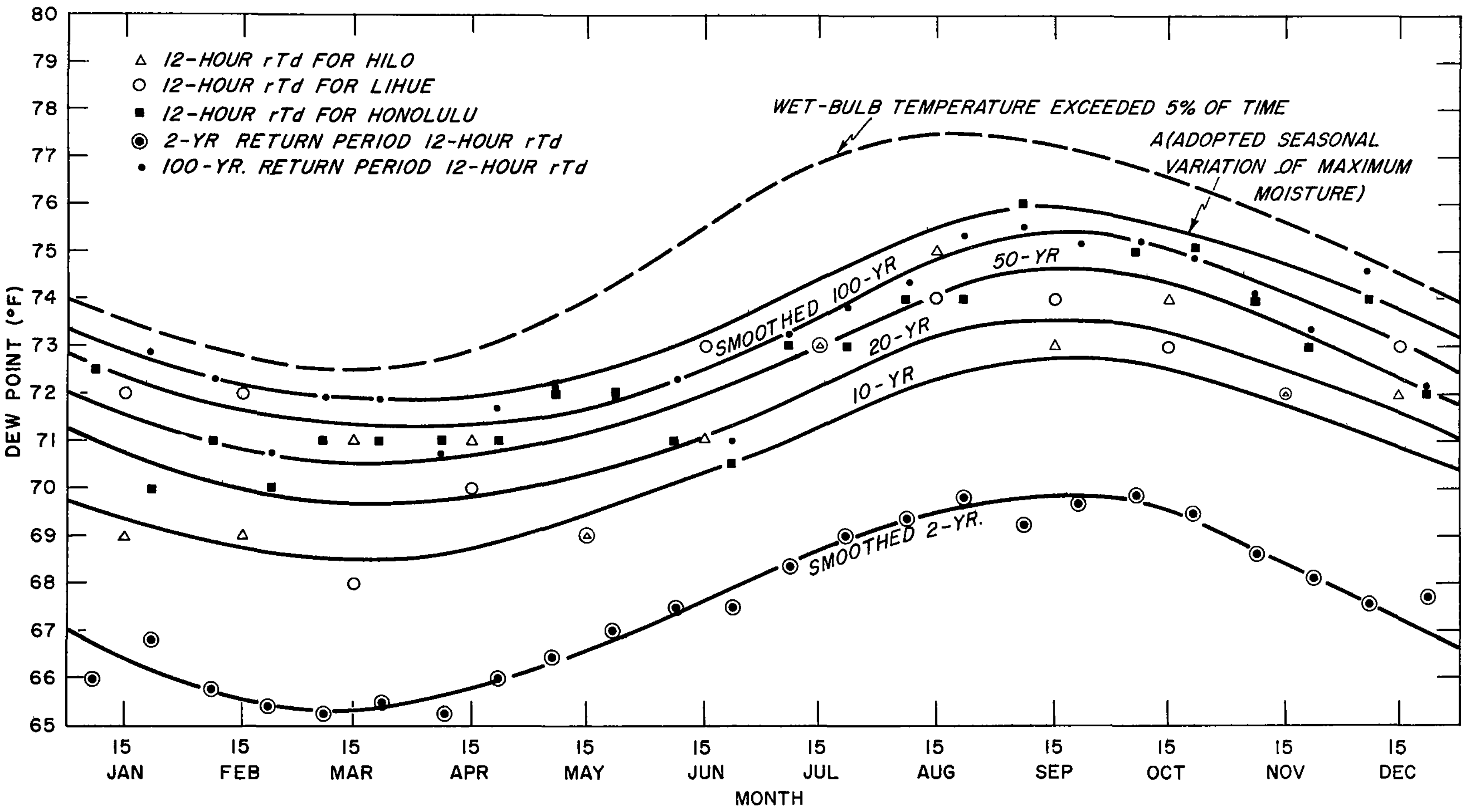


Fig. 5-13. **SEASONAL VARIATION OF MAXIMUM MOISTURE**

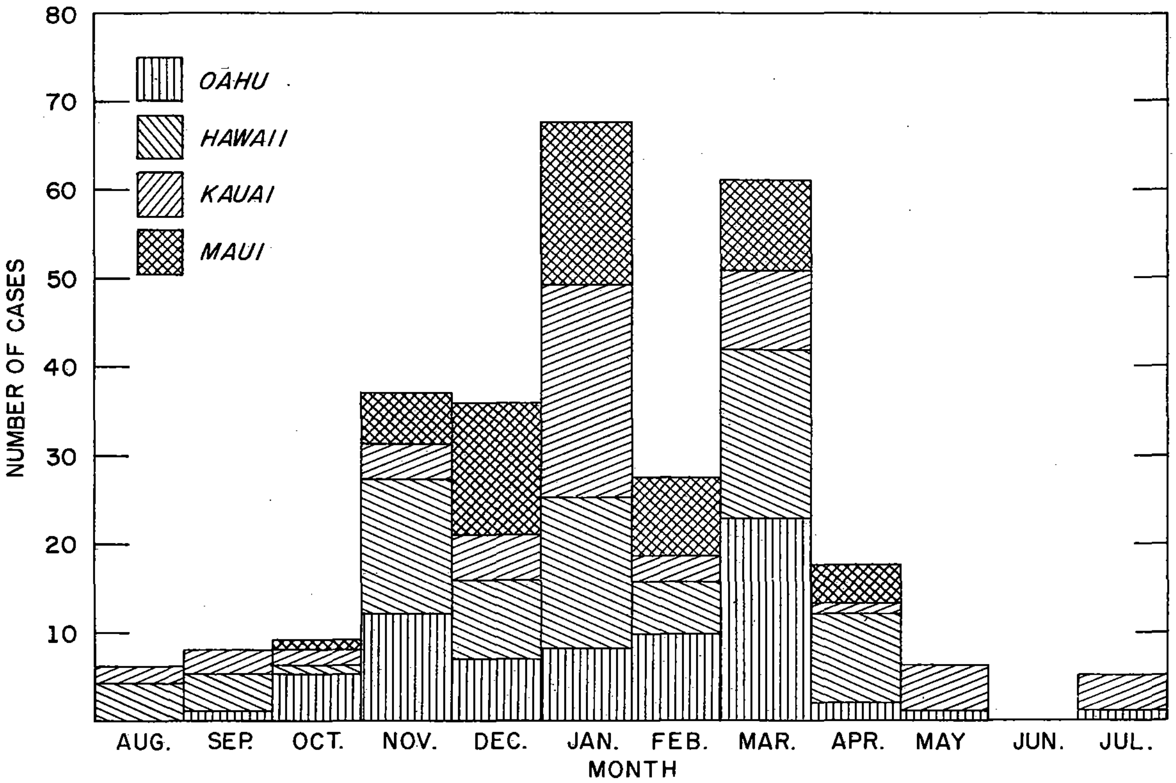


Fig. 5-14. **SEASONAL DISTRIBUTION OF ABSOLUTE MAXIMUM DAILY PRECIPITATION**

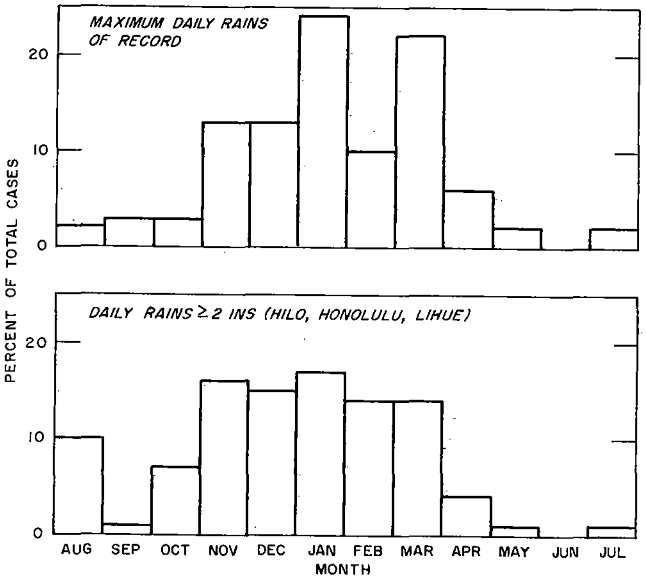


Fig. 5-15. **SEASONAL DISTRIBUTION OF LARGE DAILY RAINS**

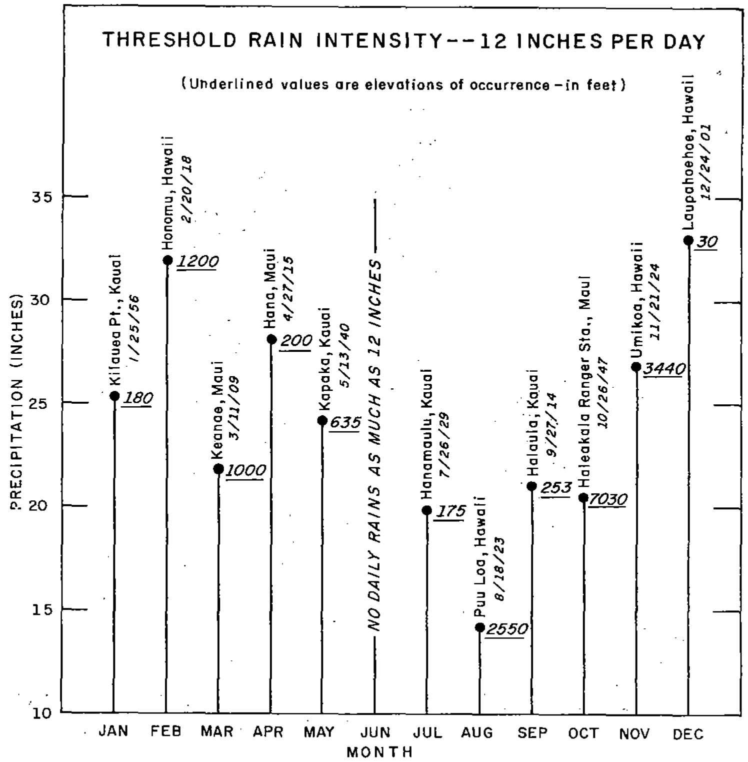


Fig. 5-16. HAWAIIAN ABSOLUTE MAXIMUM DAILY RAINS

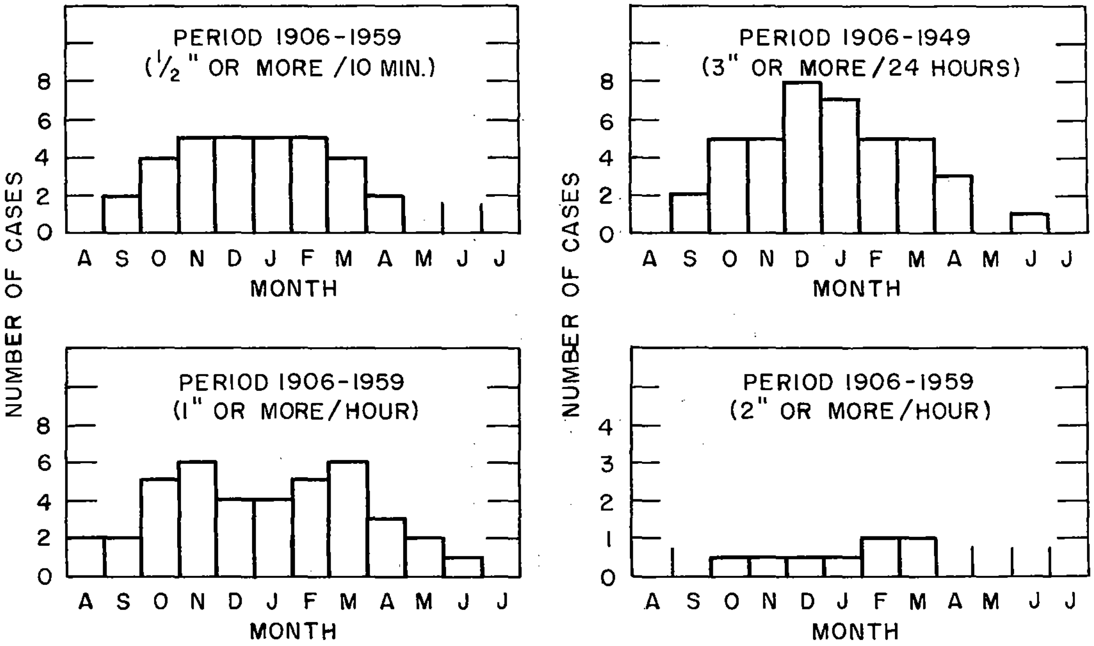


Fig. 5-17. SEASONAL DISTRIBUTION OF HONOLULU RAINFALL

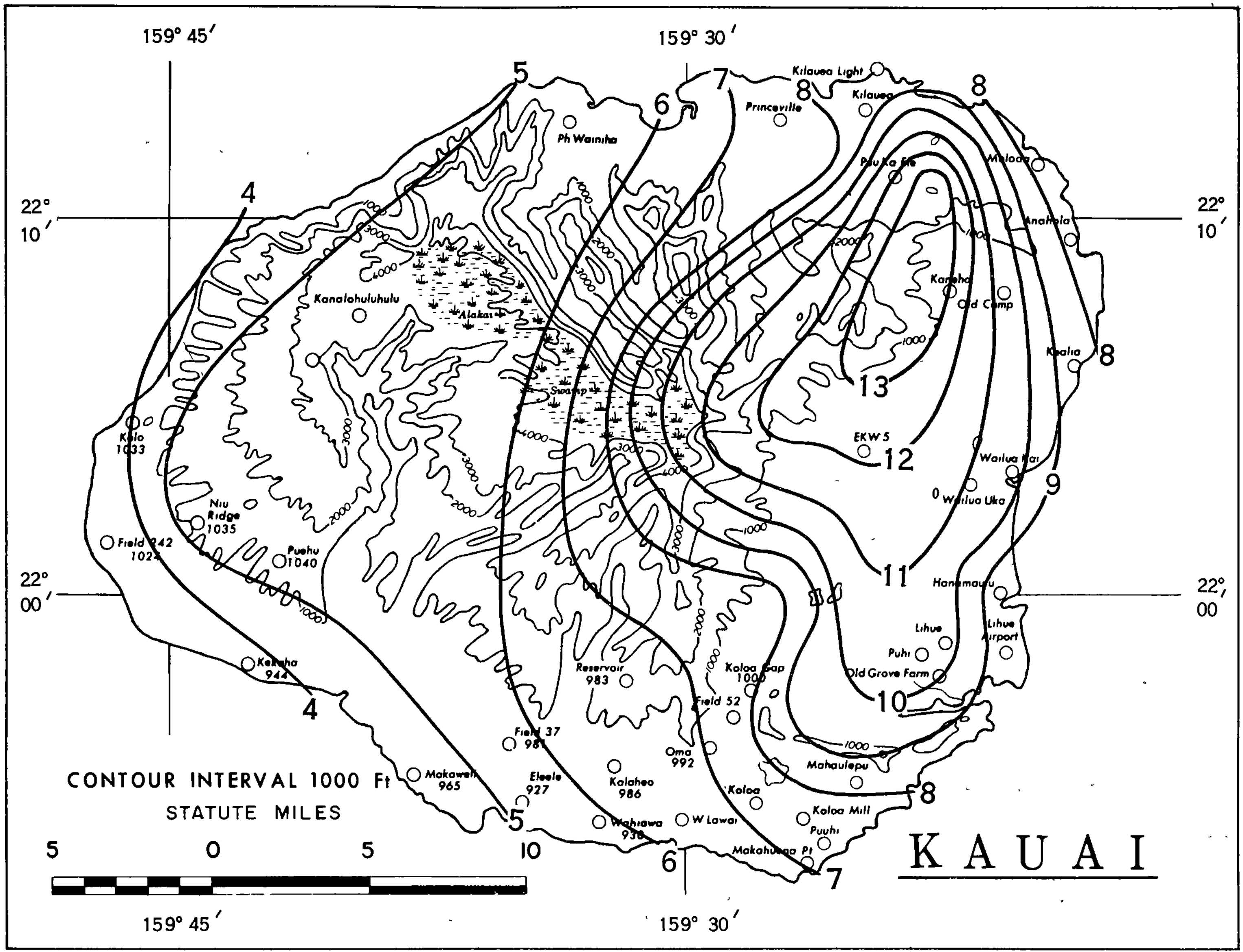


Fig. 6-1. NOVEMBER 28-30, 1954 STORM - INCHES OF RAINFALL

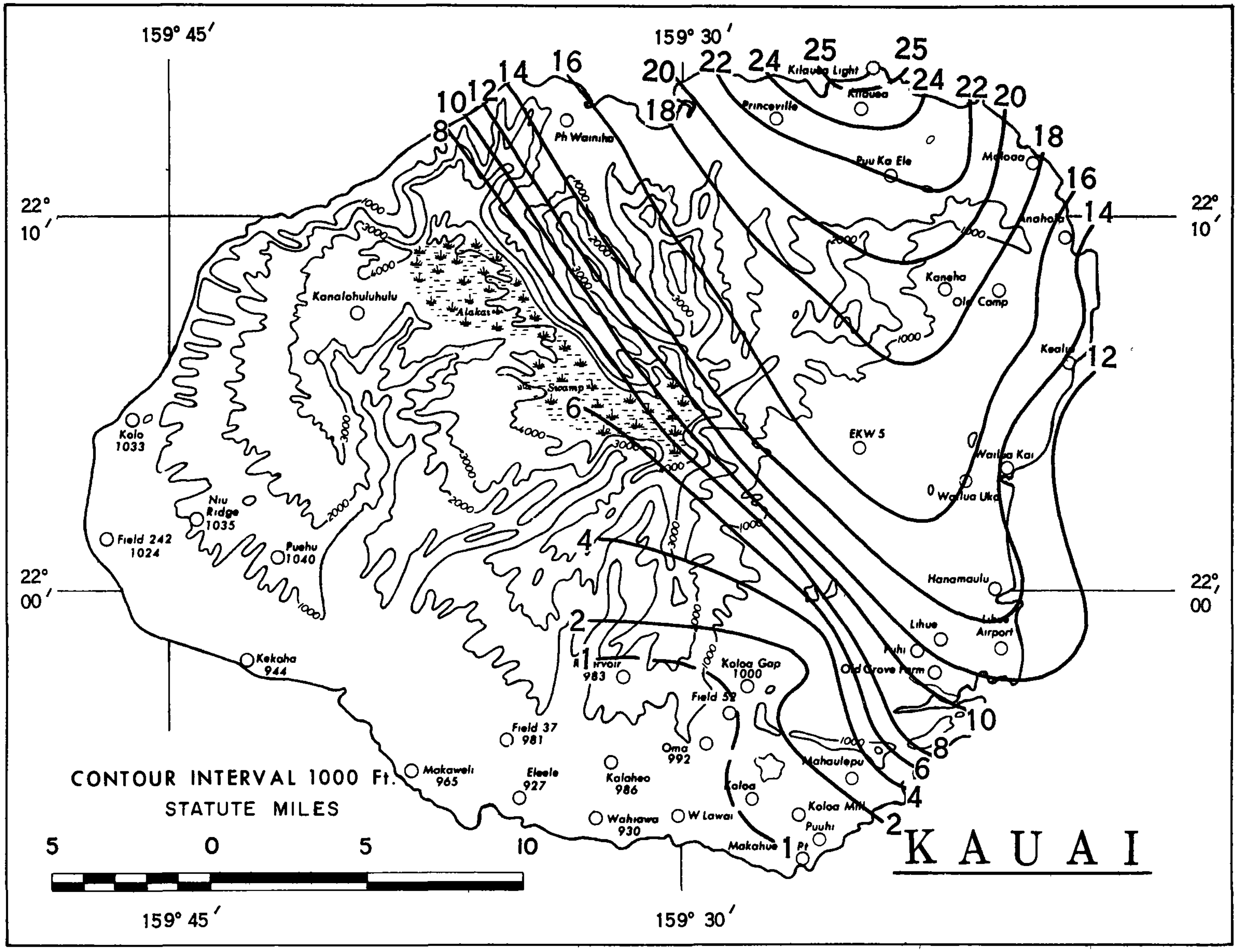


Fig. 6-2. JANUARY 25, 1956 STORM - INCHES OF RAINFALL

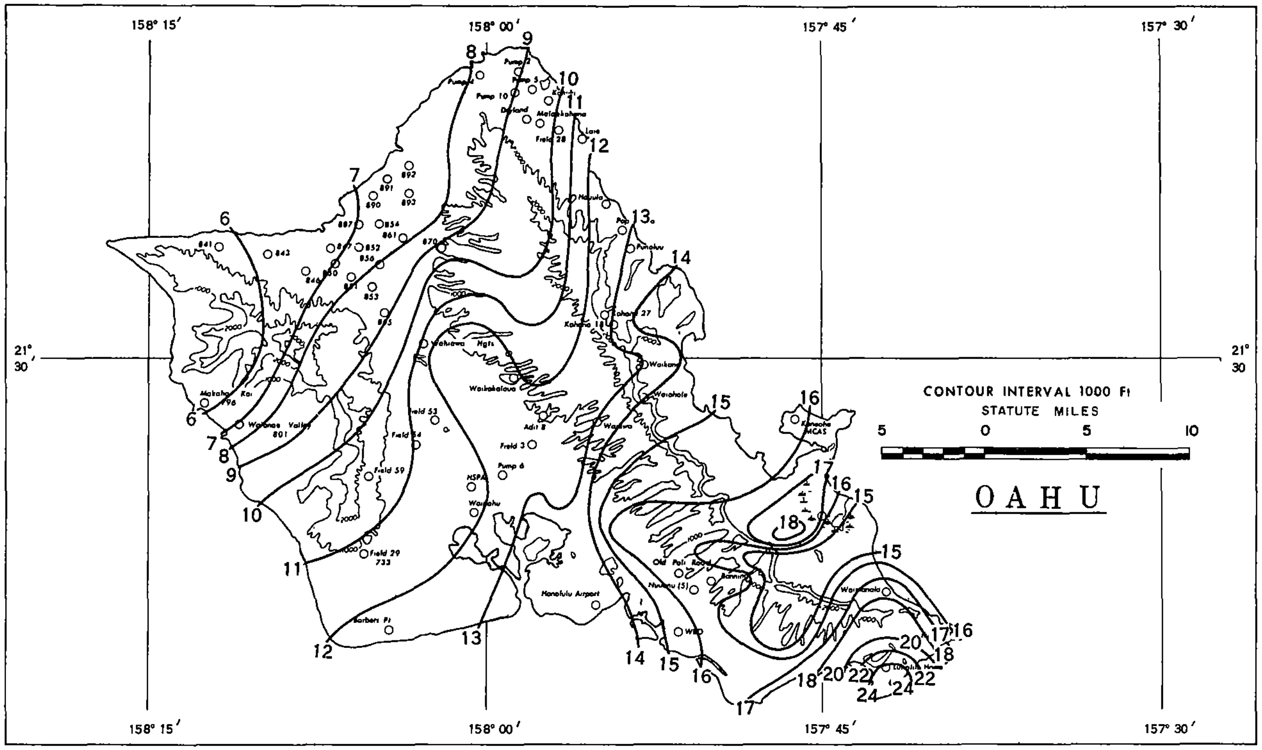


Fig. 6-3. MARCH 5-6, 1958 STORM - INCHES OF RAINFALL

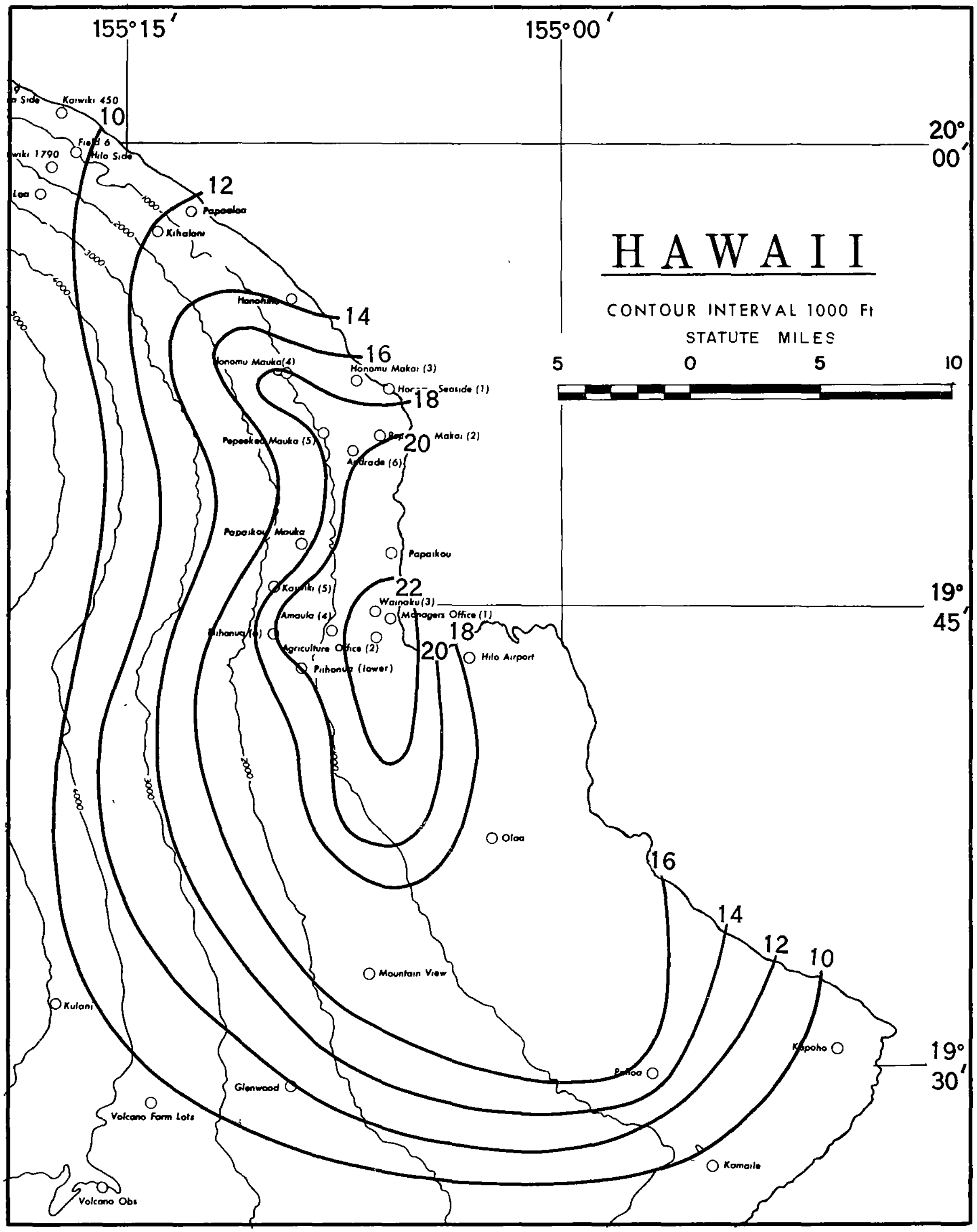


Fig. 6-4. NOVEMBER 1-3, 1959 STORM - INCHES OF RAINFALL

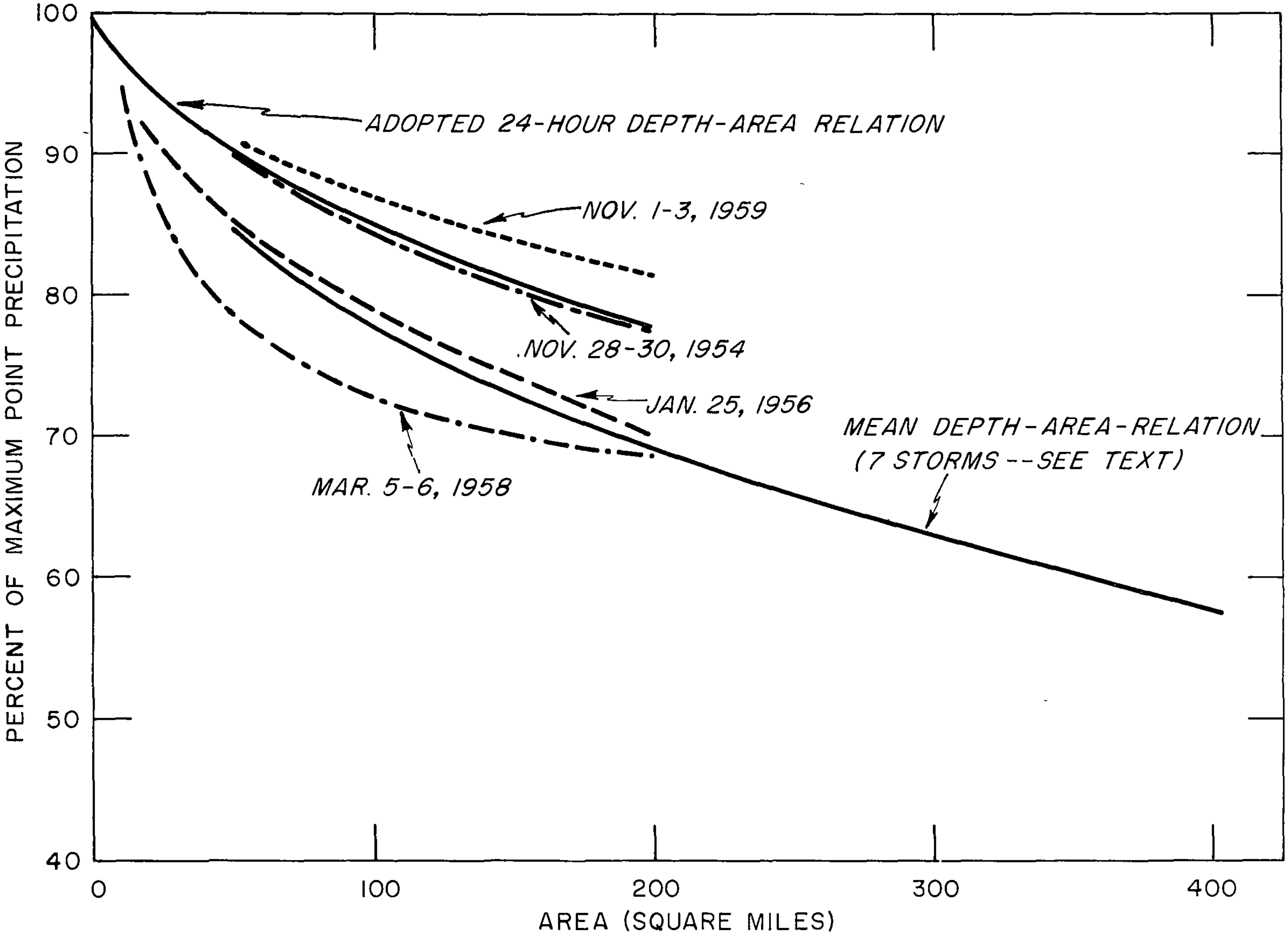


Fig. 6-5. DEPTH-AREA RELATION

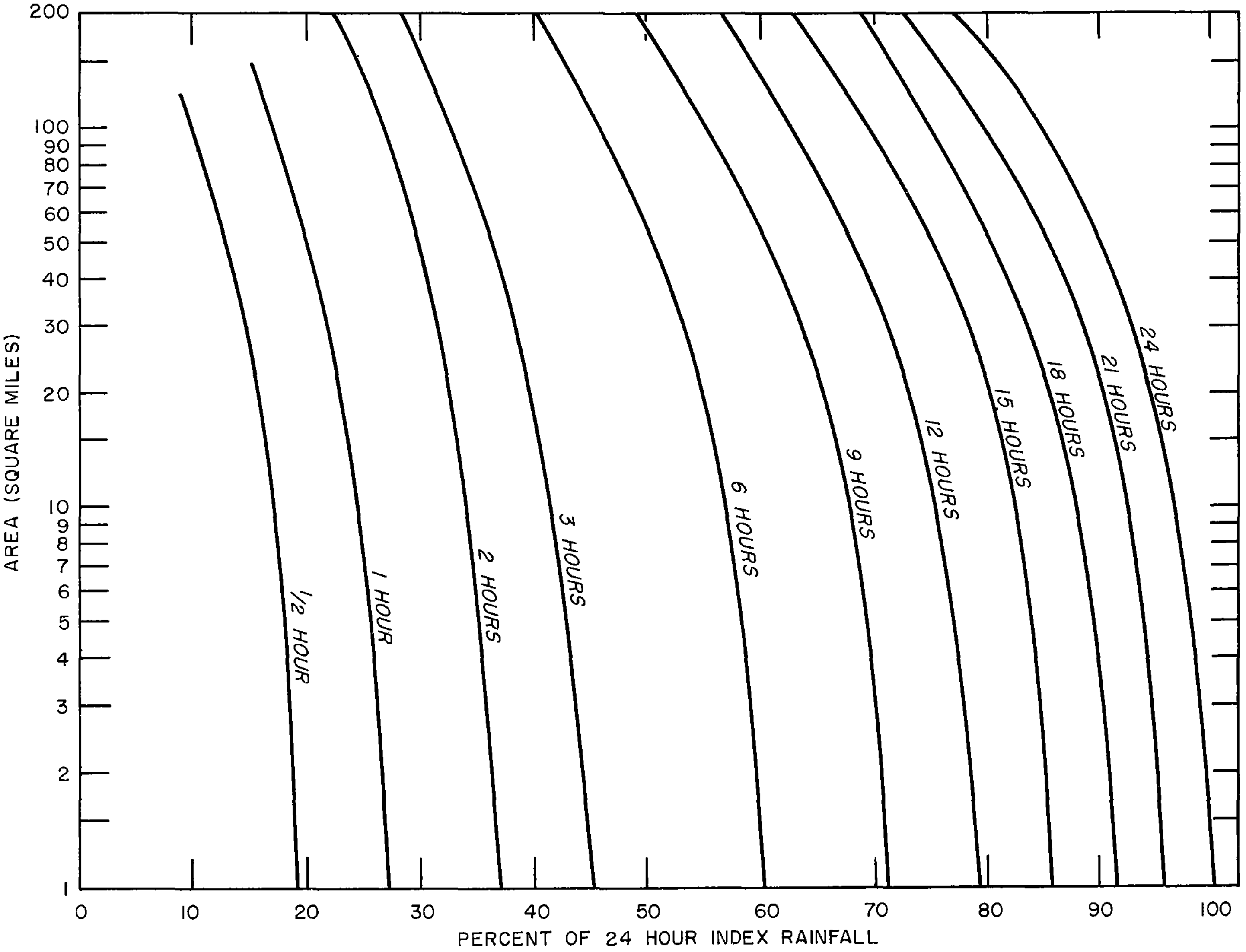


Fig. 6-6. VARIATION OF PMP WITH BASIN SIZE AND DURATION

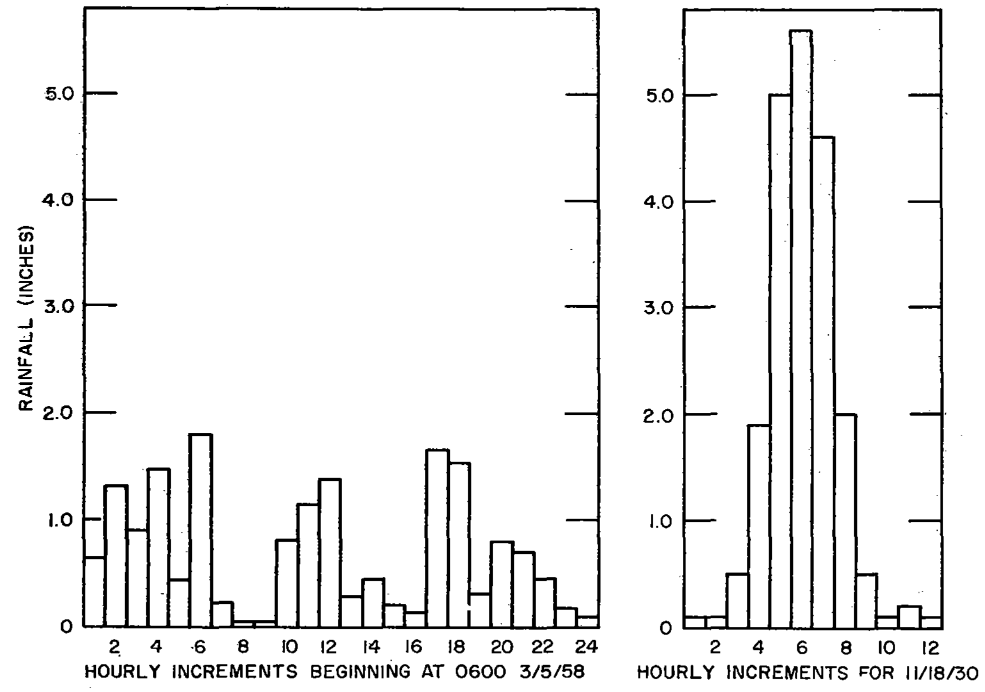
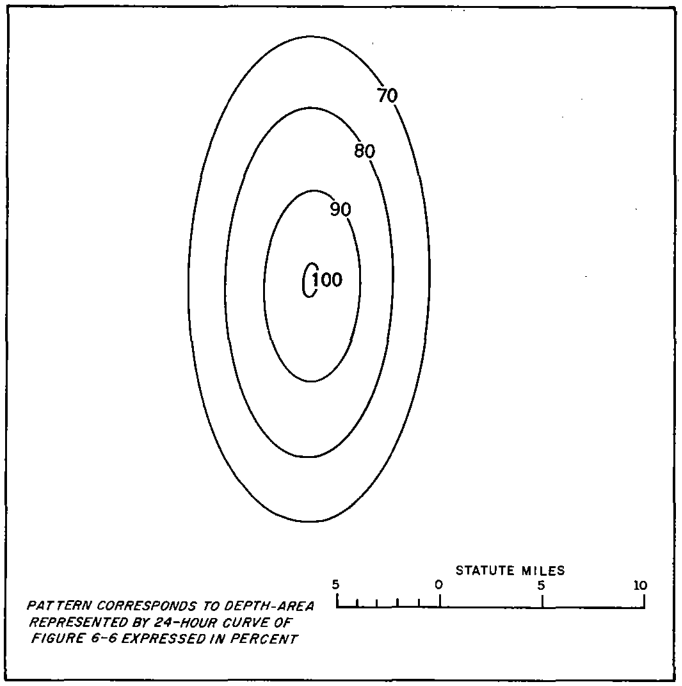


Fig. 6-7. HOURLY RAINFALL DISTRIBUTION AT HONOLULU IN 1958 AND MOANALUA IN 1930



PATTERN CORRESPONDS TO DEPTH-AREA REPRESENTED BY 24-HOUR CURVE OF FIGURE 6-6 EXPRESSED IN PERCENT

Fig. 7-1. PMP ISOHYETAL PATTERN

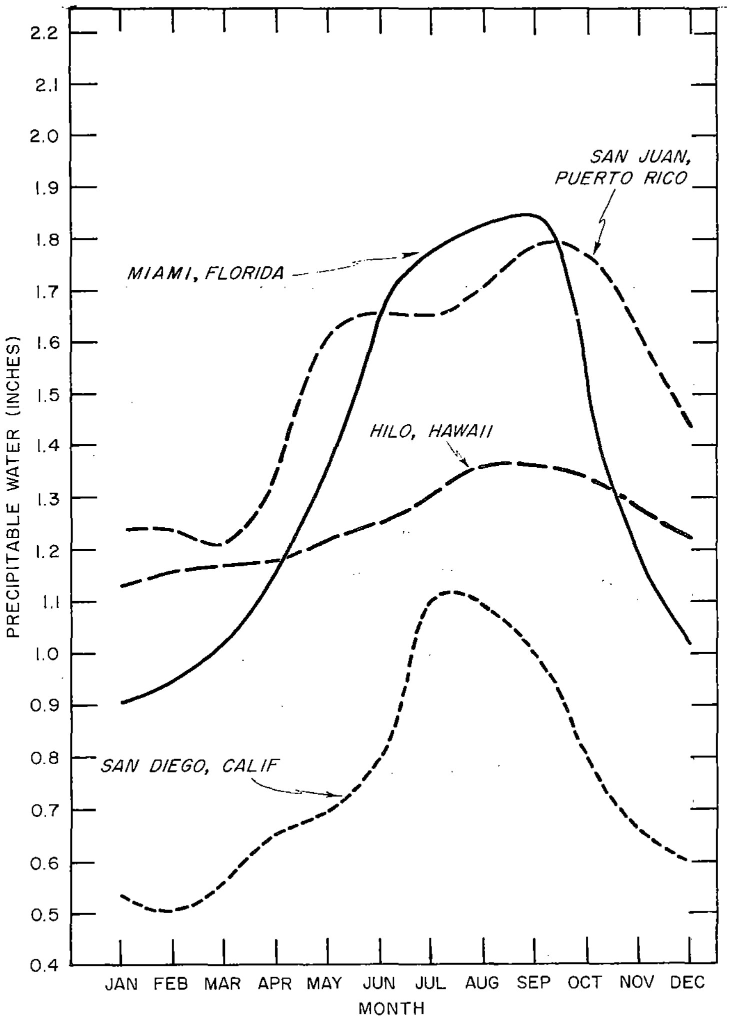


Fig. A-1. **SEASONAL VARIATION OF MEAN PRECIPITABLE WATER**

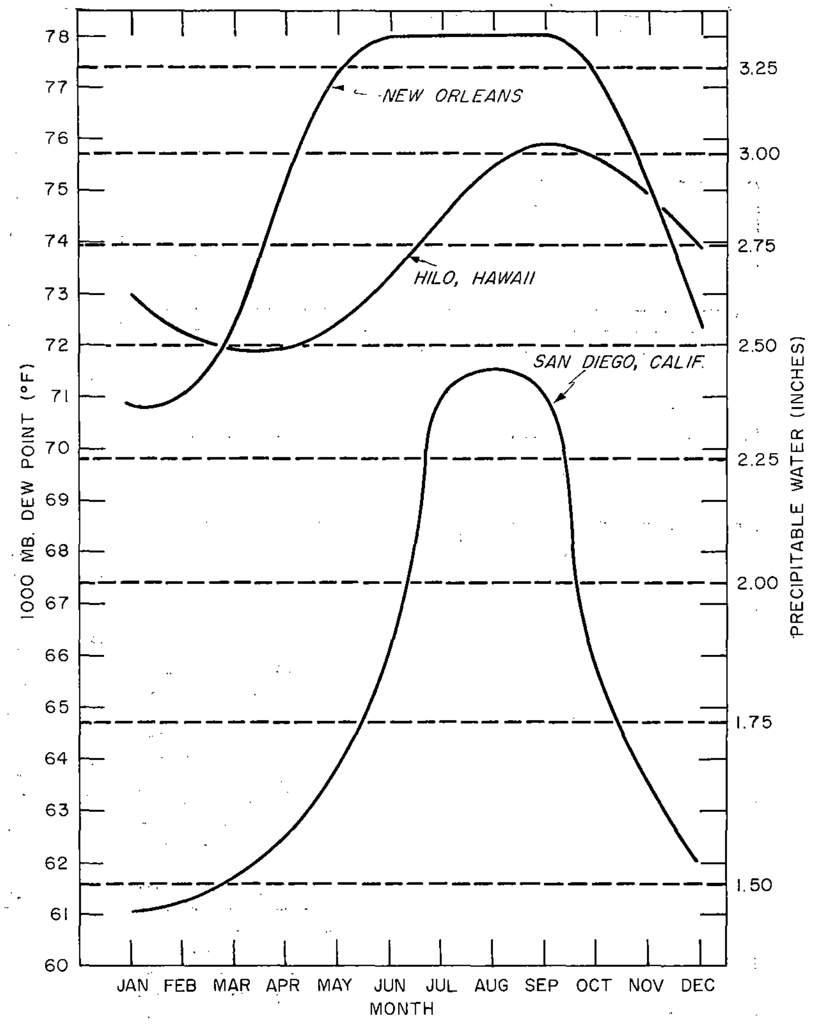


Fig. A-2. **SEASONAL VARIATION OF MAXIMUM PRECIPITABLE WATER**

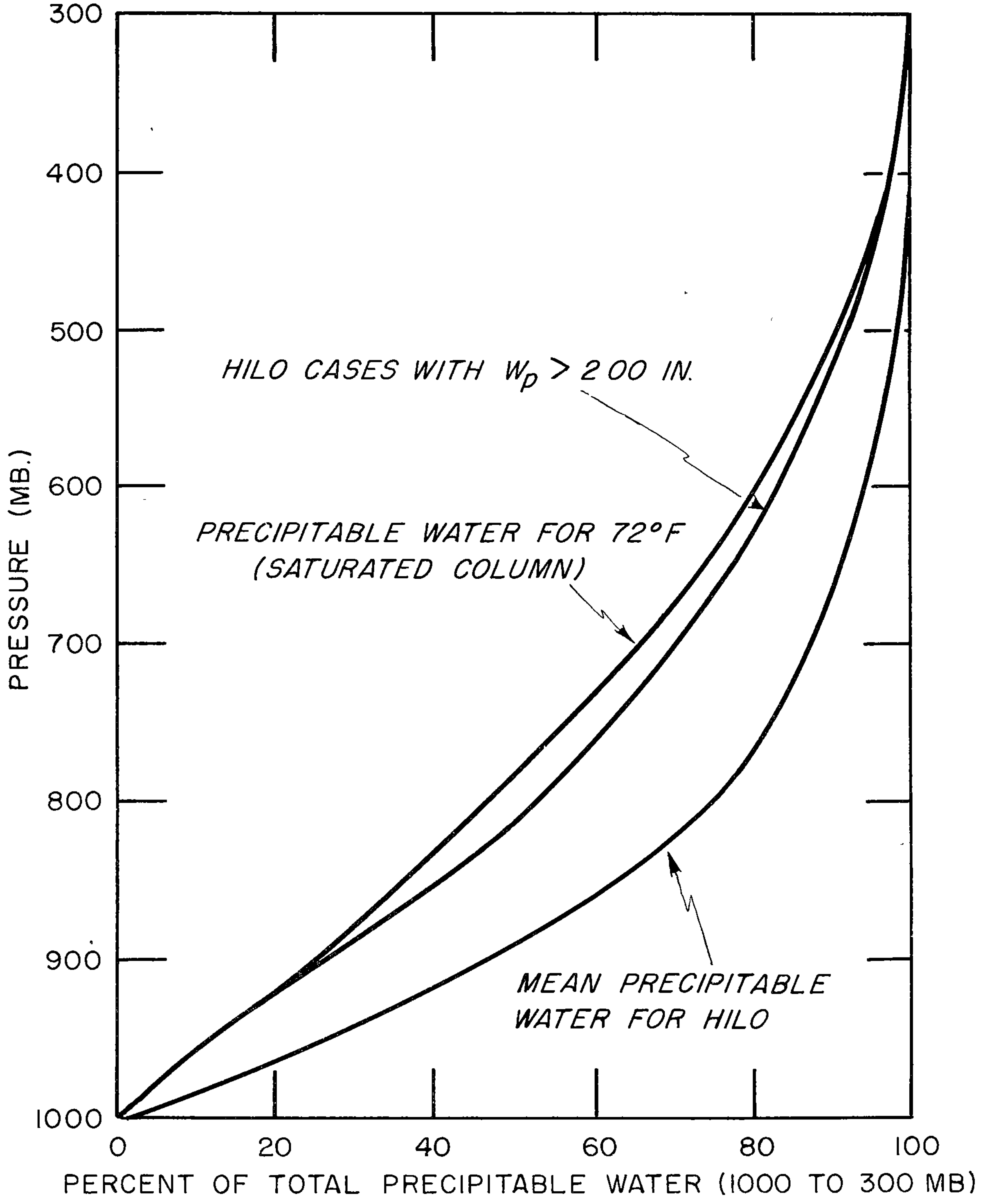


Fig. A-3. PRECIPITABLE WATER VARIATION WITH HEIGHT (PERCENT BELOW 300 MB)

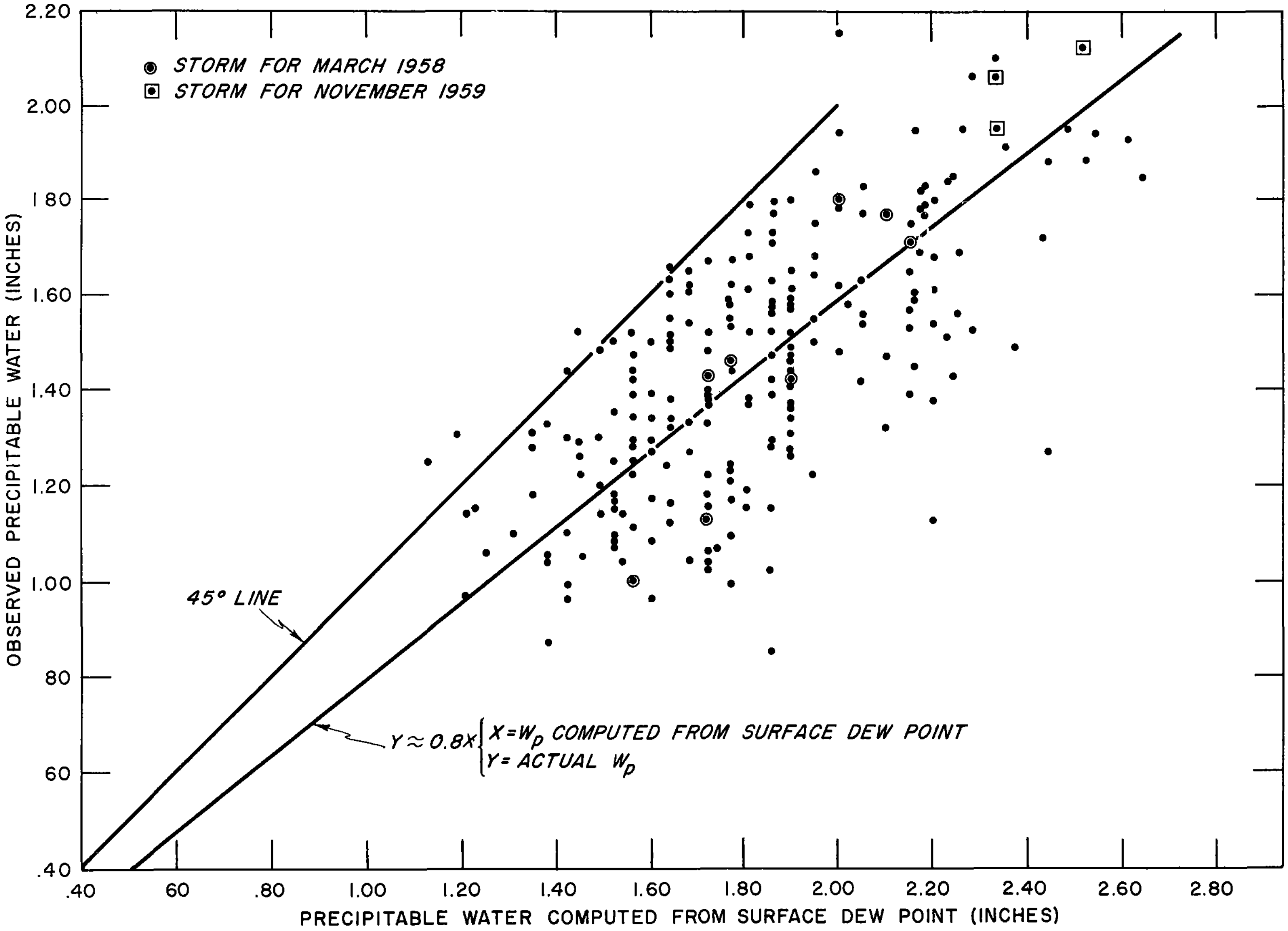


Fig. A-4. COMPUTED VS. OBSERVED PRECIPITABLE WATER FOR HILO, HAWAII (RAIN CASES)

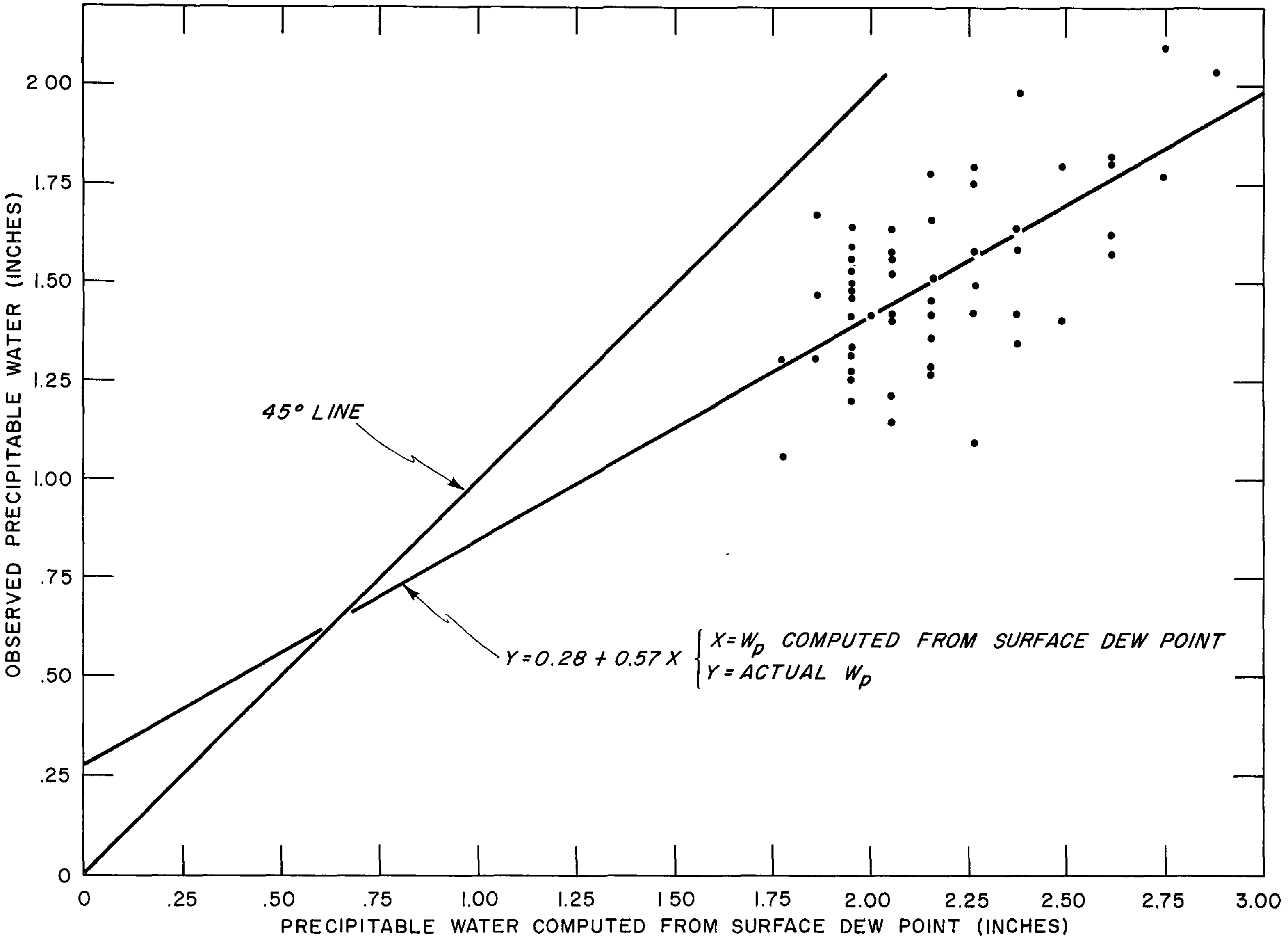


Fig. A-5. COMPUTED VS. OBSERVED PRECIPITABLE WATER FOR HILO, HAWAII - (HIGH DEW POINT CASES)

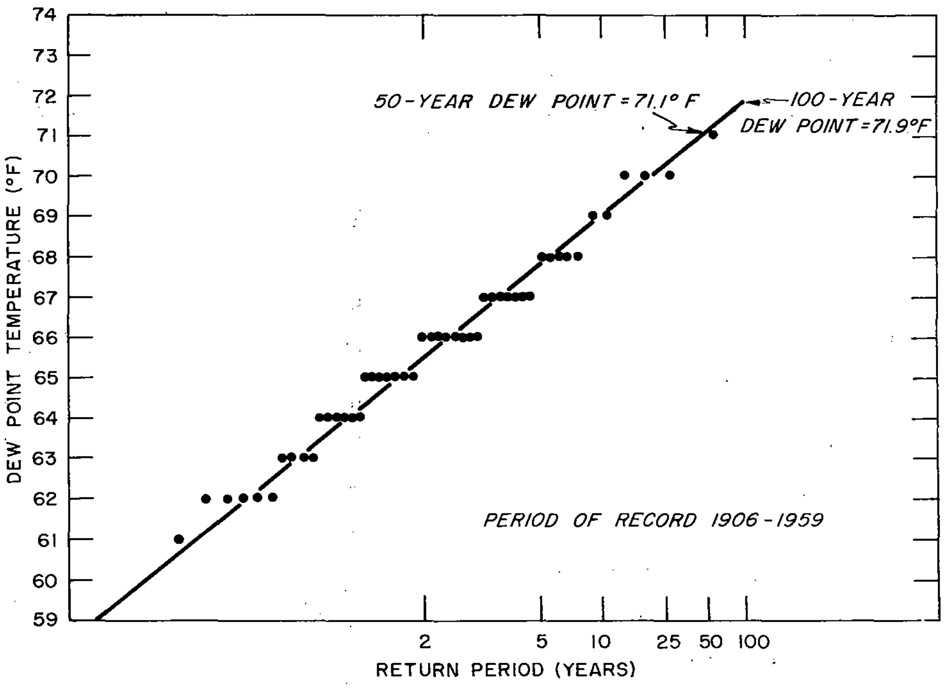


Fig. A-6. STATISTICAL ANALYSIS OF HONOLULU'S 12-HOUR PERSISTING DEW POINTS (MARCH 16-31)

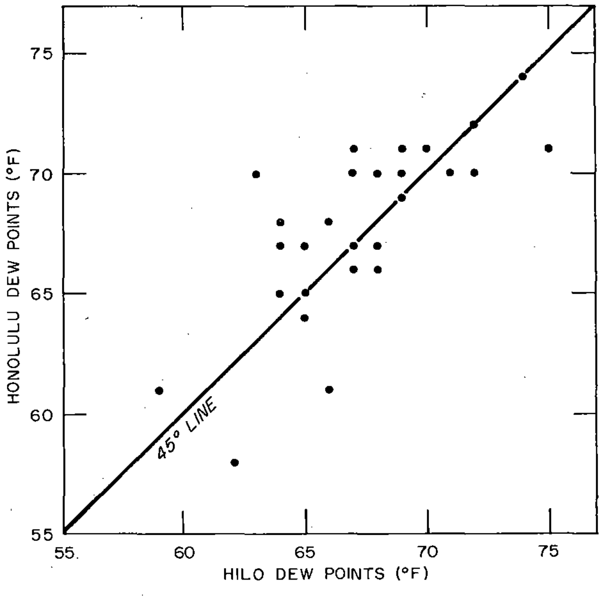


Fig. A-7. HONOLULU VS. HILO DEW POINTS FOR SELECTED HEAVY RAIN CASES

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