

A Review of Concepts in Hawaiian Climatology¹

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IN HAWAII, which is noted for its equable climate, the lack of great variations between seasons often obscures the importance of day-to-day and geographic variations in weather.

Hawaii owes its relatively uniform climate to its position with respect to the sub-tropical high pressure cell and accompanying ocean currents. The rugged topography causes salient orographic rainfall patterns. The variations in annual rainfall through short horizontal distances are common knowledge among residents of Hawaii. Areas in the mountains immediately behind Honolulu receive up to 160 inches annually, while at the seashore, 5.5 miles away from the mountains, less than 15 inches is recorded. On Kauai, the annual mean varies from 450 to 20 inches in a horizontal distance of 12 miles.

The changes of greatest economic importance, surprisingly enough, are those that occur between consecutive months and between consecutive years. The growing of pineapples and of sugar cane represents the two most important industries in the Hawaiian Islands. These industries, which utilize a large proportion of the arable land in the rainfall zone between 20 and 100 inches, have found that the wide variations in rainfall from the mean in consecutive months and consecutive years constitute one of the most critical risks in their operations.

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A program of research aimed at improvement of short- and long-range forecasts has been initiated by the sugar and pineapple industries of Hawaii in cooperation with the U. S. Weather Bureau. In the course of the work it has become clear that the investigations of Hawaiian climate in the past have been of such diverse character that a summary of present knowledge would be of assistance to those workers concerned with climatologic problems of these latitudes.

STORM TYPES

A clear-cut definition of storm types is probably somewhat more difficult than it was thought to be in the past. Besides orographic rain resulting from lifting of the trade winds, Jones (1939) stressed the importance of what he called "cyclonic activity." He asserted that what is locally known as "kona weather" in Hawaii is associated with "cyclonic" or frontal activity. The word *kona*, interpreted as leeward, bears the connotation of winds from south or west (leeward with respect to the normal trade winds). Kona weather has also been described by Daingerfield (1921) and by Leopold (1948).

Jones pictured the periods of heavy rainfall as frontal passages of the temperate latitude type. Later work has shown that many disturbances, particularly in summer, are of the subtropical character as defined by Riehl (1945). During periods when the semi-permanent anticyclone of the eastern Pacific is strong, Hawaii derives rainfall from easterly waves—low pressure troughs moving toward the west in the trade wind current. Riehl (MS.) states that "weather conditions in winter are

marked by frequent interaction between wave troughs and ridges in the polar westerlies and tropical perturbations. Especially the larger amounts of rainfall over Hawaii seem to occur mainly in periods of such interaction, while uncomplicated passages of extratropical fronts account for many of the smaller rains. Interaction between disturbances of high and low latitudes apparently is the most potent rain-producing factor throughout the trade wind belt."

In describing cyclonic storms, Jones pictured the cloud types producing winter rains as comparable to middle latitude frontal cloud systems. This is true infrequently. Hawaii seldom experiences a complete overcast of altostratus or nimbostratus clouds. In a large percentage of storm periods, the cloud systems are more like those described by Riehl (1945) in the Caribbean. On rainy days over the ocean the masses of cumulus are larger and higher than usual, built up into congestus and, occasionally, cumulonimbus clouds. Patches of altostratus are usually associated with these cumulus masses, with occasional cirrus and altocumulus clouds. Over the islands, orographic lifting assists in cloud development, and the coalescing cumuli, viewed from below, often resemble nimbostratus. From afar it can be seen, however, that only segments of an island are under a complete overcast.

In summary, the rainfall usually comes from large but discrete cloud masses mostly of cumuliform type. A rainy day is characterized by increased size and number of cumuliform clouds. These changes result from horizontal convergence to the east (the rear) of the axis of an easterly wave and in association with a trough in a westerly current.

STORM TYPES IN RELATION TO RAINFALL

Studies of weather types correlated with rainfall amounts in Hawaii have been made by Huddleston (MS.) and by Wallen and Yeh (MS.). In both cases the authors used the Northern Hemisphere Surface Synoptic Chart

Series. Huddleston used the precipitation recorded at Honolulu and the CIT-AAF³ classification system (1942). He also had available the 3 km. maps accompanying the Northern Hemisphere surface charts.

Huddleston showed that the best correlations with Honolulu rainfall were obtained with a type he called "No. 31," characterized by "purely zonal flow at the surface" with a series of cyclones moving eastward along the Aleutian chain. The 3 km. level is characterized by "weak circulation with the base of the upper trough extending as far south as the Hawaiian Islands . . ." Though his explanation is not very clear, his map gives the impression that the situation involves the passage over Hawaii of a polar trough of the type described by Riehl (1945). Huddleston's second important rain-producing type is his No. 22, "Meridional circulation . . . [with a] well developed Pacific High" positioned over the ocean 20° off the Oregon coast, and a "semi-stationary low center" northeast of Hawaii at about 30° N., 150° W. The abnormally high latitude position of the Pacific High is associated with a low index, and some frontal systems or troughs may move at relatively low latitudes over Johnston Island and Hawaii, stagnating in the semi-stationary trough northeast of Hawaii. The passage of these troughs over Hawaii would account for the correlation of the map-type with rainfall.

Wallen and Yeh (MS.) set up a surface map-type classification scheme which expressed the geographic relation of frontal systems and high pressure cells to Hawaii. The Hawaiian area was inspected on the daily Northern Hemisphere surface charts and the maps were classified for a 25-year period. The two main categories of their classification scheme were described as "anticyclonic" and "cyclonic." The former placed a high pressure cell NW or NE of Hawaii giving surface winds over the islands NE or ESE. The cyclonic situations were characterized primarily by westerly surface winds

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over the islands with a low center to the NW, N, or NE. Their "anticyclonic" situations are clearly the normal or trade wind weather. They showed that the frequency of the two types varied inversely: the cyclonic was greatest in the December–February period while the anticyclonic was greatest in summer.

Because winter is usually the rainiest season and also the one when cyclonic storms are most frequent, Wallen and Yeh had expected to find a correlation between a yearly precipitation index for Hawaii and the frequency of cyclonic situations for the same year. This correlation, however, was not revealed by their data. They concluded that variations in trade wind rainfall are sufficiently important to mask any direct relation of total rain to the frequency of cyclonic storm types.

The importance of local convective clouds has generally been overlooked in view of the obvious importance of trade wind orographic rain. Leopold (1948) analyzed the time of day of rainfall occurrences on Oahu and Lanai and showed that the leeward or drier portions of these islands receive, primarily, afternoon rainfall. Stations on coasts exposed to the trade winds and those directly in the lee of the mountains receive nighttime rain predominantly, a characteristic of orographic rain in Hawaii (Loveridge, 1924; Jones, 1938). The afternoon maximum was interpreted as resulting from local convective clouds which build up over the drier areas with daytime heating of the ground surface.

Another characteristic type of rain in Hawaii is that of the "naulu storm" (Leopold, 1948), a summertime cumulus congestus or possibly cumulonimbus, which may produce short-duration, high-intensity rainfalls over leeward or dry portions of the islands. The naulu rains result from local convergence where the sea breeze meets the trade wind.

PROBLEMS AND TECHNIQUES IN ANALYSIS

In the analysis of map types, a difficulty which occurs in low latitudes is that the historic series of weather maps does not give sufficient

detail on the various low latitude disturbances which have been defined in recent years.

Riehl's studies in Puerto Rico (1945) can be applied with profit to synoptic analysis in the Hawaiian area. An important tool used by Riehl and others for synoptic analysis in these latitudes is a time cross section of winds plotted to the maximum observed height. Pressure and temperature data are also plotted at standard levels. Slight changes in winds, pressures, and temperatures will often show the passage at high levels of minor troughs which may go undiscovered or be poorly defined on the weather maps.

Using a similar type of chart, Stidd (MS.) noticed that in the winter months no rain fell in the drier localities of Hawaii as long as the trade winds were present in the lowest 2,000 or 3,000 feet. Each occurrence of rain was preceded by an almost total disappearance of the trade wind. A positive correlation between rainfall and surface pressure tendencies was also demonstrated, the rainfall occurring in conjunction with rising pressures. Situations in which the axis of the nearest high pressure cell was passing to the east of the station as it sloped toward the equator with height were more productive of rain than those situations in which the axis was passing to the west. This is in accord with general knowledge of the distribution of convergence and divergence about the high cell.

Another aid to synoptic analysis made use of the vast number of weather reports from airplanes flying Pacific routes (Stidd, 1948). This is essentially a graph of time versus distance along a given route, the plane reports being spotted in their appropriate positions. Points of minimum "delta value" (true altitude minus pressure altitude) were found to lie on nearly straight lines in the summertime. The positions of these lines were found to correspond to the positions of easterly waves and the slopes of the lines were a function of the speed of such waves. The full use of all pilots' reports is a time-consuming operation, however, and a thorough test of this method has not yet been made.

Mordy and Leopold (MS.) found highly significant correlation between trade wind rainfall on Oahu and the temperature at 300 mb. (about 30,000 feet msl.) on the Honolulu sounding. This is particularly interesting because trade wind rain falls from clouds whose tops ordinarily do not exceed 10,000 feet msl. Recent studies by the authors indicate that the 300 mb. chart is probably the most important tool in forecasting rainfall in the Hawaiian area.

GEOGRAPHIC DISTRIBUTION OF RAINFALL

Mean annual rainfall maps for the various islands in the Hawaiian group, which improve on the Oahu annual map of Voorhees (1928), are available in the Territorial Planning Board Report (1939). The only monthly isohyetal maps available are median rainfall maps for Oahu prepared by Halstead and Leopold (1948), based on an 11-year period, 1936-1946.

Tüllman (1936), in a study of rainfall distribution over the central and western Pacific, prepared mean annual rainfall maps for the Hawaiian islands of Kauai, Oahu, Maui, and Hawaii. His monthly and annual means were generally based on the 20-year period from 1905 to 1924. The records of those stations which did not coincide with that base period were adjusted. His data came from the published records in *Climatological Data*. Tüllman did the work in Germany and apparently did not have access to Voorhees' map.

Tüllman's isohyetal maps are sketchy, but his graphs of the annual march of rainfall at various stations are of interest. The mean rainfall for each month was plotted on a time-versus-precipitation graph for each station having the requisite records for direct use or adjustment to the 20-year base.

The Weather Bureau, in the publication *Climatological Data*, groups the stations of each island in geographic units selected primarily to divide windward from leeward stations. Oahu, for example, is divided into six areas. Using the stations within each of these geographic units, Tüllman compared qualitatively the curves showing the annual march of rainfall at each

station and grouped together the stations which had similar curves. This provided two or three groups within each geographic unit. Those stations lying in the same elevation zone had similar annual march curves.

It was unfortunate that Tüllman did not discard the arbitrary geographic units of the Weather Bureau and lump all stations having similar annual march curves. He would thus have been able to delineate, on various islands, zones which are similar in distribution of rainfall during the year. This would be one indication of similarity in rainfall processes. In a single given month there are large differences between the mean rainfall for each island; moreover, during a given storm, geographic units having apparently similar exposure may record widely different rainfall amounts. The problem of determining areas of similar rainfall processes is, therefore, not as simple as might be expected. Delineation of such areas is important in the problem of developing techniques for both short- and longer-term quantitative rainfall forecasts for various portions of each island.

Tüllman's group curves can be analyzed and consolidated to provide the recapitulation mentioned. Only moderate accuracy could be expected, however, because he did not publish the numerical rainfall data in tabular form with the curves. Quantities could be determined only as accurately as the small-scale curves could be read.

The most striking features of the annual march curves are the exceptionally low mean rainfalls for certain months. All groups of stations for Kauai show a low rainfall in February, as low as, and in some cases lower than, the mean for June. Yet January and March tend to be among the months of highest rainfall. This depression in February means is apparent to a lesser extent in all curves for Oahu, in those for the northeast slopes of west and east Maui, and for the northeast coast of Hawaii.

Radical increase in rainfall in November over October appears on the northeast coast of Ha-

waii at all elevations, and in the high rainfall zone of east Maui at elevations of 3,000–4,000 feet.

The northeast exposures of both east and west Maui and the high rainfall zone of eastern Hawaii show marked rainfall minima in June, October, and February. The same zones generally show sharp maxima in August, December, and April. Yet leeward Hawaii and Maui, all of Oahu, and all of Kauai exhibit no such striking behavior.

The 20-year period on which Tüllman based his mean rainfalls is sufficiently long to be considered fairly representative. The curves for certain of his groups might not have contained enough stations of long record and thus the adjustment procedure may have significantly affected their representativeness. Yet the consistency of these variations between certain areas lends credence to them.

An unpublished study by the authors (Stidd and Leopold, MS.), using more recent data, reaches conclusions which are in agreement with Tüllman's findings. This study discusses two individual components of Hawaiian rainfall and shows that their annual cycles are quite different. The cycle of cyclonic activity is shown to have a winter maximum and a summer minimum while the cycle of orographic activity is found to have a three-phase annual cycle with minima in June, October, and February. These minima correspond exactly to the minima of rainfall found by Tüllman in the very wet regions of Maui and Hawaii.

The study also shows that mean monthly rainfall distributions have the same type of pattern as the mean annual distributions, the only fundamental differences being in spacing and values of the isohyets. A quantitative statement of these two variables is shown to define adequately the rainfall distribution and magnitude for any mean month.

The study implies that the pattern of mean annual rainfall can, as an approximation, serve as the pattern for rainfall over any given period

of time, and quantitative daily forecasts of rainfall based on this approximation are now being made.

Because of the skewness of the frequency distribution of monthly rainfall values, the arithmetic mean is a poor statistic to represent normal values of Hawaiian data. The occurrence of abnormally wet months causes the mean rainfall values to be significantly greater than median values. Landsberg (MS.) showed that median monthly rainfall values for Hawaiian stations reach stability in a shorter period of record than do means. But he noted that for an island as a whole, "the pattern of isohyetal maps . . . if medians are used, shows no material difference in areal distribution compared to maps using mean-value isohyets. The difference is one of absolute values, not a shift in the location of drier or wetter areas."

The greatest monthly and annual values of precipitation are obviously in the mountain area. Annual means vary from 450 inches on Mount Waialeale to less than 10 inches on the lee side of Maui. Studying the Honolulu area, Voorhees (1928) found the correlation coefficient between mean annual rainfall values and station elevation to be only +.21; correlating annual mean with distance from the mountain crest gave a value of —.81. The maximum rainfall area in the Koolau Range on Oahu, average elevation 2,000 feet, lies about a mile leeward of the mountain crestline. The Koolau Range is long and narrow and is oriented perpendicularly to the trade wind.

The essentially conical-shaped mountain ranges of central Kauai and west Maui reach maximum elevations of about 5,000 feet. In both instances the maximum rainfall zones coincide with the maximum elevations. Yet on the higher (10,000–14,000-foot) conical mountains of Haleakala (east Maui), and of Mauna Loa and Mauna Kea (Hawaii), the zone of greatest annual rainfall is on the windward side at elevations of about 3,000 feet, a fact noted by both the Territorial Planning Board Report (1939) and Jones (1942). Leopold (MS.) attributes

the different elevations of maximum rainfall to convergence resulting from horizontal splitting of the trade wind by the higher mountains.

It is stated in the Planning Board Report (1939) that only in the Kona area (western portion of Hawaii) does the summer rainfall (May to October) exceed that of winter. However, Tüllman's curves, checked by current investigations of the authors, have disclosed that some of the wetter areas on Oahu and Hawaii have summertime maxima.

Correlations between the wind direction aloft (10,000 feet) and the geographic distribution of rainfall were made by Wallen and Yeh (MS.). Though their conclusions are tentative, they indicated that relative to the direction of wind at 10,000 feet the rainfall maxima appeared on the lee side of islands and the minima on the windward sides. Though this at first seems contrary to the expected orographic effects, Wallen and Yeh present a qualitative picture of distribution of convergence and divergence which might explain the observed rainfall pattern.

Riehl (MS.) studied 10 years of daily rainfall records at 21 rain gages in north central Oahu. He delineated four districts which approximately coincide with the areas known locally as Waimea, Waialua, Wahiawa, and Helemano. At the outset he defined "effective" precipitation as rain of 0.10 inches in a day at a given station. In summer 20 per cent of the total rainfall occurs in showers of less than 0.10 inches in a day and is, therefore, ineffective. In winter only a negligible amount is ineffective. Of the total *number of days* of rain, 40 per cent in winter and 60 per cent in summer are ineffective. For the remainder of his study, only "effective" rain was considered. He then defined a "rainstorm" as one which "in each of the four districts half or more than half of the stations received [effective] precipitation." He concluded that 80 to 90 per cent of the total precipitation occurs in "rainstorms."

Isohyetal patterns of mean monthly rainfall due to "rainstorms" show higher rainfall over

the mountains than over the plains. In other words, orographic lifting is an important factor determining rainfall distribution in general storms.

Riehl found that rainstorm precipitation is more evenly distributed from mountain to plain in summer than in winter.

MONTHLY AND ANNUAL VARIATIONS IN RAINFALL

Variations in yearly values of rainfall for Oahu stations were studied by Nakamura (1933). As an index of this factor he computed the ratio of standard deviation to mean annual rainfall for each of certain stations. Isoleths of this index showed that the smallest year-to-year variation occurred in the high rainfall zones of the mountains and the largest variations in the leeward, drier areas.

Landsberg (MS.) found that for 11 Oahu stations, every month of the year had had, in one individual year or another, the smallest monthly rainfall total in the year. As a measure of the skewness or asymmetry of the monthly rainfall frequency distributions he computed the value $\frac{\text{median}-\text{mean}}{\text{mean}}$ for each of the 12 months,

at a given station. By averaging the ratios for the 12 months, each station would be represented by an index of asymmetry. These values for each of 22 Oahu stations plotted on a map showed that the greatest asymmetry occurred in lower leeward stations, and the least in windward and mountain stations. This is similar to the coefficient of variation computed by Nakamura and described above, and it checks his geographic distribution.

Another indication of the smaller variations in rainfall at higher stations is provided by Wentworth (1946), who studied the inter-station correlation of amounts of annual rainfall on Oahu. Annual rainfall values at various pairs of stations were expressed as ratios, year by year. Wentworth computed the mean ratio between pairs of stations as part of an analysis of the frequency distribution of these ratios.

The best correlated pairs of stations had a probable deviation from their mean ratio of less than 10 per cent. For those pairs having poorest correlation, the most probable deviation in a single year was 45 per cent. The best correlated pairs were found among the high rainfall stations, while the low rainfall stations showed the greatest deviations.

Wentworth's study is important also to students of hydrology. He showed how the interstation correlations could be used to synthesize missing annual rainfall amounts at stations whose records are sufficiently long to establish the initial correlation. The method provides indices of reliability for such interpolated records and could be used on monthly as well as annual values.

Riehl (MS.) found a double maximum of effective precipitation in both summer and winter, as had Landsberg (MS.) and Tüllman (1936). Riehl attributes the minima in June and September to the seasonal shift of the subtropical ridgeline in the high troposphere. This ridge is centered over the latitude of Hawaii in June and September, having moved north in midsummer and southward again in the fall.

Secondary maxima of rainfall in winter are not due to a change in the number of storms, of which there is a single maximum in winter. Riehl concludes that at the beginning and end of the winter season there is the greatest possibility of interaction of summer-type tropical disturbances with the extra-tropical winter storms. This leads to the double maximum of rainfall in winter.

Riehl finds that 80 to 90 per cent of the total rain occurs in the general storms or "rainstorms." From this he concludes that present forecasting techniques which should allow the forecasting of these storms are sufficient to solve the main problems of agricultural forecasting for Hawaii.

The cyclic behavior of rainfall has been studied by a number of workers. Cox (1924) constructed an index of monthly rainfall values based on 10 stations and extending over 44 years. He concludes that a cycle of 3.7 years

appears to exist and is even stronger than the annual cycle.

Johnson (1946) analyzed yearly rainfall amounts at one station, Kualapuu, Molokai, by the method proposed by Alter (1937). Wentworth (1947) in reviewing this work concisely describes the method as "a process of finding that constant interval between pairs of years such that the average difference in rainfall between the two members of a pair is a minimum."

At Kualapuu, the 20-year periodicity was the strongest, and the 12-year cycle was second strongest. For the Honolulu record, a 14-year cycle appeared most probable with the exception of cycles of 36 years and certain others too close to the length of the 66-year record to be very reliable. Using the "Honolulu Rainfall Index" (the average of the percentages of the annual mean for 10 stations in the Honolulu area), Wentworth (1947) applied Alter's method to find the most probable cycles in the annual values of this series. He showed that the 16- and 20-year cycles were the most promising.

Working with the monthly values of rainfall at Waimanalo, Landsberg (MS.) showed by harmonic analysis that the annual variation is a wave which is not accidental. He decided that the existence of other periodicities in the data for that station was not probable.

The fact that the lengths of most probable cycles differ among stations or groups of stations in the islands markedly reduces the usefulness of, if not the confidence in, such cycles. Wentworth's analysis was the most practical. He showed that the average deviation of the "predicted" rainfall index from the actual can be reduced by using the 20- and the 12-year cycles. In individual years, however, the difference between actual value and the mean value was less than that between the actual and the value predicted by use of the cycles. Wentworth concludes, therefore, that "for practical purposes, any statistical, long-run gain is canceled by the evident risk of an aberrant estimate for a given year."

If, on the other hand, it can be shown that for certain specific purposes a reduction in average error of estimate outweighs the importance of very large errors in estimate for individual years, application of the technique should be considered.

The work of Solor (1948) has opened up new fields for the growth of longer-range forecasts for Hawaii. Having classified individual months on the basis of average rainfall for the Territory of Hawaii and on the average number of days of rain, he segregated monthly mean surface pressure maps for the Pacific area. The anomalies of mean pressure for individual months from the long-time average pattern were distinctly different for wet and dry months. Wet months are characterized by higher than normal pressure in the Aleutian area and a weak low in the mean pressure field over Hawaii. Dry months, on the other hand, have abnormally low pressure near the Aleutians and higher than normal pressure over the Hawaiian Islands.

Because there is some month-to-month persistency in the patterns most different from normal, these pressure anomaly patterns have some forecast value. Solor found that near-normal pressure distributions apparently have no significant persistence and the forecast value is dubious.

This distribution of anomalies fits the general knowledge of Hawaiian rainfall. Wet months, at least in winter, are characterized by a dislocation of the Pacific high and the admittance of cyclones to more southerly paths.

Riehl (MS.) interprets the import of Solor's correlations of pressure patterns and rainfall as follows: Mean monthly pressure patterns do not indicate deviations from average conditions which "would tend to raise or suppress rainfall throughout the month. They denote a basic state of the general circulation favorable or unfavorable for generation of a few potent disturbances."

Another possible forecast tool is provided by the work of Yeh (MS.). He found that there is some general relation between the latitude

of the belt of maximum west wind at 10,000 feet (the jet stream of Rossby) and precipitation in Hawaii. When the jet stream lies south of 40° N. Lat. on a given day, the probability of rainfall over Hawaii is small. Positions between 50° and 60° N. apparently are associated with higher rainfall probability.

WINDS

Most of the older studies of upper air data over the Pacific are of little significance in the development of forecast techniques. Beals (1927*b*) presented wind roses for various levels above Pearl Harbor, later extended to higher levels by Thomson (1928). The latter showed that the west winds, which surmount the low-level trade wind easterlies, reach lowest elevations in March and April on the average, while the height of the easterlies is greatest in May and June.

Beals (1927*a*) showed that the surface wind at Honolulu progressively changed in mean direction from northeasterly to a more easterly flow between 1905 and 1924. Wentworth (1949) has brought this study up to date and finds that in the last decade the earlier trend has been reversed, the mean winds gradually backing to a more northeasterly direction.

The diurnal patterns of wind have been discussed by Beals (1927*a*), Henry (1925), and Leopold (1948). In summary, sea and land breeze regimes control the wind direction in the lowest levels on the protected coasts of all the islands.

Leopold (1948) noted that the line along which the sea breeze meets the trade wind is associated with the development of a cloud line on Lanai, Molokai, and northeastern Hawaii. Diurnal changes in cloudiness in many areas are related to the development of sea and land winds. The regime is particularly apparent along the Hamakua (northeast) coast of Hawaii where drainage winds from Mauna Kea keep the slope clear at night; during the day the sea breeze reinforces the trades and causes an afternoon maximum of cloudiness.

At Honolulu and on the easterly coast of Oahu the surface wind is normally easterly at all hours with a maximum speed in the afternoon and a nocturnal minimum. Leopold (1948) relates this to surface stability at night. He showed that at Honolulu winds between 1,000 and 2,000 feet have a maximum speed at night. This, apparently, is caused by horizontal convergence as the subsidence temperature inversion reaches its minimum height at night.

CLIMATE IN RELATION TO CROPS AND VEGETATION

Maps of the areas covered by different vegetal associations have been compiled by Ripperton and Hosaka (1942).

There is evidence of change in vegetation in certain areas, the most prominent being noted in the Waimea area of Hawaii where many square miles formerly in heavy forest now constitute a grassland containing large amounts of an introduced cactus. A local wind storm, known as "mumuku," is said to have decreased markedly in frequency between 1830 and 1856. The change was attributed to the introduction of cattle and subsequent modification in vegetation (Anonymous, 1856 and 1926).

In a series of papers, Das (1928, 1931 *a,b*) analyzed the relation of monthly sequences of temperature and rainfall to the production and quality of sugar. High-quality cane juice was apparently correlated with high temperatures during the first summer after planting and with cooler weather in the winter prior to harvest. Rainfall should be relatively low during the winter season and relatively high during the summer to produce the best quality of cane. Das found that a wet August in the summer prior to harvest was strongly correlated with high yield.

BASIC DATA

Few areas of comparable size have the large number of rain measurements made in Hawaii. Approximately 900 rain gages, most of which are kept by sugar and pineapple plantations and

by cattle ranches, are currently installed. About three-fourths of these gages are read daily. The data from 205 are published as daily values in *Climatological Data*; in addition there are 79 stations for which monthly values only are published. A survey of basic rainfall data being collected currently has been made by Leopold, Burn, and Stidd (1948).

Surface wind observations are few except on the island of Oahu and the only upper wind data are collected by the Weather Bureau from Honolulu.

For studies of phenomena of the lowest 4,000 feet of the atmosphere, the location of the Honolulu Airport from which the Weather Bureau radiosondes are flown is poor. With respect to the trade winds the office is about 8 miles leeward of the Koolau Range, whose peaks in this vicinity reach 3,000 feet.

Forecasting at Honolulu is very dependent on reliable and continuous upper air observations at the existing ship stations and on Midway and Johnston Islands. Full use of pilot reports, particularly in summer, will probably become more essential as improved techniques develop.

DIRECTION OF FUTURE WORK

The strong geographic patterns of rainfall totals should make the development of a scheme for quantitative short-range rainfall forecasts relatively simpler than in many other places. On the other hand, significant differences between apparently similar areas on different islands loom large as potential difficulties. Four directions of work are necessary: (1) the definition of criteria for expressing the strength of pressure troughs locally affecting the Hawaiian Islands; (2) the correlation of these criteria with rainfall quantities; (3) inter-correlation of rainfall between different stations or localities; and (4) an improved understanding of the structure of the high troposphere and lower stratosphere.

To attain these ends certain groundwork is required. In connection with quantitative measures of the importance of various upper air

factors influencing rainfall, a series of well-analyzed upper air charts together with time-height sections of wind and radiosonde data must be collected. Past maps available at the Honolulu Weather Bureau office only partially fit this need. After teletype sequence data are destroyed, plotting of the necessary time-height sections is made difficult.

Correlation of rainfall values with the upper air data and inter-station correlation require better organization of the basic rainfall data. In January, 1948, a scheme for routine collection of all rainfall quantities in a centralized location was initiated by the Pineapple Research Institute and the Hawaiian Sugar Planters' Association Experiment Station.

The attainment of longer range forecasting techniques is apparently in sight as a result of Solot's work and that of the Extended Range Forecast Section of the U. S. Weather Bureau. For the best use of such forecasts the same problems of inter-station correlation are met, this time with monthly rainfall values. Month-ahead rainfall forecasts made by the Weather Bureau for Hawaii are now being tested by selected sugar and pineapple plantations.

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