The Role of Climatology in the Hawaiian Sugar-Cane Industry: An Example of Applied Agricultural Climatology in the Tropics[1]

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CLIMATOLOGICAL STUDY in the Hawaiian sugar-cane industry has a long, noteworthy history. Meteorological observations on the plantations were initiated in 1883, preceding the establishment of the first official weather bureau station in Hawaii by fully 20 years. The climatological network in the cane-growing areas expanded by leaps and bounds to 50 stations at the turn of the century, and to 500 stations in 1960 in an area of only 350 sq miles (Fig. 1).

In the late 1920's and early 1930's Das (1928, 1931*a*, 1931*b*, 1932) used the rainfall and temperature records to define the effect of climate on crop yield and juice quality in a simple, direct manner. He also advocated the use of day-degree as a guide to irrigation control (Das, 1936). Investigations along the same line of climate-and-plant complex were carried further by Williams (1933), Borden (1940, 1949), Clements (1940), Swezey (1942), and others into the early 1940's.

At the end of World War II meteorologists, freshly relieved from their wartime duties, were able to turn their attention to a multitude of peacetime problems. The Hawaiian sugar industry promptly seized this opportunity. The Experiment Station and the Pineapple Research Institute founded their joint Meteorological Department in 1946 and contracted with a group of meteorologists at the University of Chicago to investigate dynamic and regional climatology of Hawaii. The culminating results of this intensified research were a series of papers in the Meteorological Monographs, discussing the general circulation, weather types, local flow patterns, rainfall statistics, and the like. Such studies inevitably led to the improvement of forecasting and furnished valuable information for operational planning.

At the half-century mark, when weather modification was a new subject, the industry embarked upon an intensive study of cloud seeding. Leading scientists from seven research institutes in the U.S.A. and abroad participated in the so-called "Project Shower." It was hoped that the Hilo coast, with its humid trade winds, would provide an ideal environment where rainfall could be induced by the addition of chemicals to the warm clouds; it was soon realized, however, that scientific know-how of artificial rainfall was probably still decades away. The project nevertheless produced valuable information in the field of cloud physics.

Realizing the limitations upon man's ability to modify weather on a grand scale, the industry sought instead to improve the efficiency of water use through the study of micrometeorology. In 1957 an evapotranspiration project was initiated at the Experiment Station. Apart from its obvious application in irrigation planning, the determination of potential evapotranspiration provides a vital link for solving the energy budget and water balance equation in the soil-plant system. The solution of these equations renders the climate-and-yield relationship amenable to quantitative treatment.

Climatological study in the Hawaiian sugar industry thus encompasses a wide variety of topics. More than 50 papers have appeared in a dozen scientific journals. The industry ranks among the leaders in the study of agricultural meteorology. The experience gained during the past three decades may very well benefit research workers in other parts of the world, especially those in the tropics. This paper attempts to summarize these studies. It is hoped that such a stock-taking will not only serve as a reminder of our past accomplishments but also as a guide-post for planning future research.

TRADE-WIND WEATHER

The subtropical high pressure cell in the Pacific Ocean with its attendant trade wind is the

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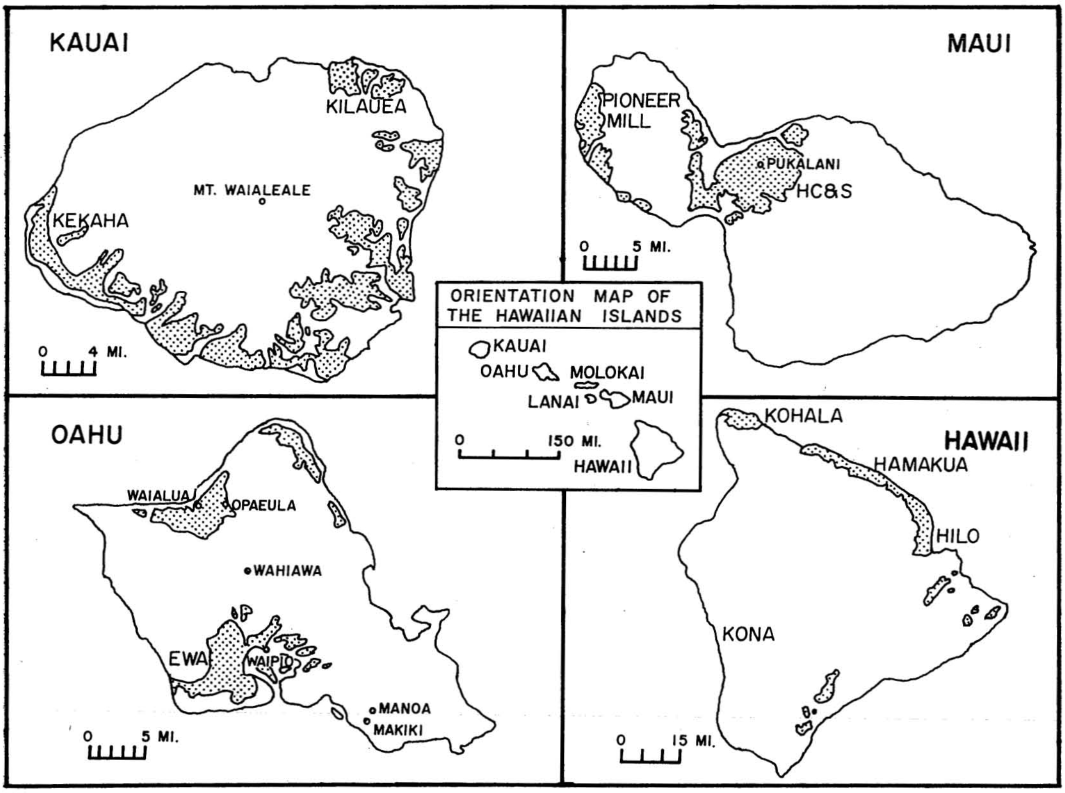

FIG. 1. Location map.

basic circulation in Hawaii; all other weather types are perturbations in this basic current. The eastern portion of a subtropical anticyclone is characterized by divergence and subsidence and consequent adiabatic heating and pronounced dryness aloft. There is, however, a mixing layer near the surface where the air in contact with the cold ocean currents becomes cold and humid. These two layers of air are separated by a zone of temperature inversion which, along the California coast, occurs at an altitude of about 1,500 ft. Downstream, toward the west, as water temperature rises and subsidence weakens, the trade-wind inversion reaches a height of about 6,000 ft in Hawaii.

Figure 2 shows the vertical structure of trade wind in Hawaii. The air below the inversion is moist, with a mixing ratio of 12–15 gm/kg at the ground surface. In the absence of orographic uplift this moist air is a poor rain-producer because the trade inversion acts as a lid to oppose the development of convective clouds; therefore, in lowland areas, the trade wind is atmospherically moist in terms of humidity but ecologically dry in terms of rainfall.

The air below the trade inversion has a lapse rate close to dry adiabatic. It requires only a little uplifting to produce rainfall. Baer (1956) has demonstrated theoretically that if the relative humidity is approximately constant below the inversion layer, rainfall would increase with height exponentially up to the base of inversion. The logarithmic distribution of rainfall with height is a unique climatic feature in Hawaii.

The prevalence of trade-wind weather in Hawaii is dependent upon the location and strength of the Pacific subtropical anticyclone. In July and August, when the subtropical ridgeline in the high troposphere is located to the north of the islands, the trades prevail during 97% of the time (Yeh et al., 1951*a*). In winter, when the subtropical anticyclone moves southward, the frequency of trade-wind weather decreases to 40–50% (Fig. 3).

OTHER WEATHER TYPES

During one-third of the year, when the trades are not prevalent, weather in Hawaii falls into two general types: mixed and cyclonic. The mixed type is characterized by the presence of an essentially east-west polar front north of the islands. This type is a very poor rain-producer as the front is located at a distance. The mixed type often ushers in cyclonic weather.

Cyclonic weather occurs in Hawaii during 22% of the year. The cyclonic weather may be further divided into four subtypes: (1) extra-tropical cyclones, (2) *kona* storms, (3) easterly waves, and (4) tropical cyclones or hurricanes. The first two subtypes occur most frequently in winter while the latter two subtypes are primarily summer disturbances.

Uncomplicated extratropical cyclones occur only when the zonal westerlies move southward into the tropics. They are, however, weakened on their journey southward and produce only small rains. Some of these cyclones reach only the northern island of Kauai.

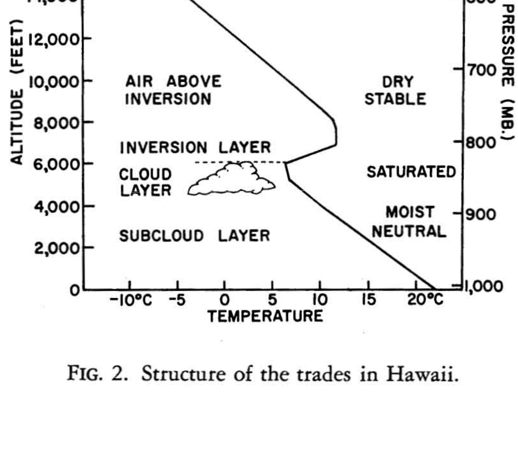

FIG. 2. Structure of the trades in Hawaii.

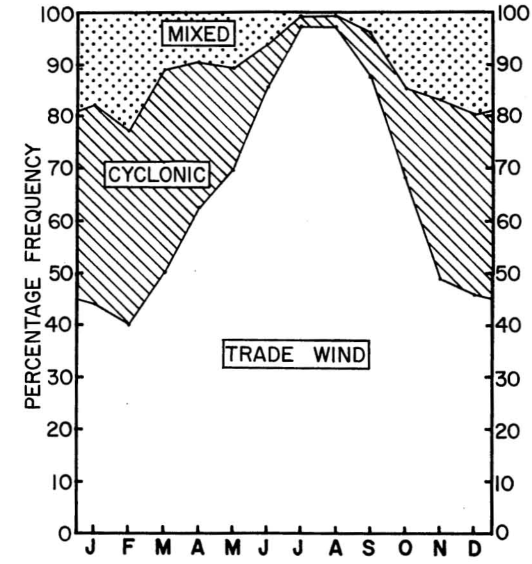

FIG. 3. Monthly variation of frequencies of three weather types.

The *kona* storm is essentially a cold-core low developed in the tropics. Simpson (1952) has described two main processes in its formation: (1) the transformation of mid-latitude cyclones which have been trapped at low latitudes by blocking action of a warm high; (2) the cyclogenesis in the easterlies triggered by the building down of a pre-existing cold upper low usually at the southern extremity of a polar trough. Once formed, all *kona* storms seem to assume the same characteristics. The term *kona* indicates that the wind during such a synoptic period is southerly. *Kona* storms occur about three or four times a year, bringing heavy rainfall throughout the islands. In the dry lowland areas they may account for more than half of the annual rainfall.

The occurrence of winter cyclones and *kona* storms in Hawaii is closely related to the general circulation. Yeh et al. (1951*b*) have shown that winter rainfall in Hawaii increases as the latitude of the jet stream increases, unless the latter penetrates to the latitude of the islands themselves. They explained that when the jet stream is weak and far to the north, Hawaii will experience a period of low zonal index. Low index flow pattern is characterized by large meridional flow and frequent interaction between tropical perturbations and troughs in the westerlies.

On a hemispherical scale the mid-tropospheric westerlies are composed of roughly sinusoidal waves. In winter an upper air trough is climatologically anchored off the east coast of Asia. The location of the next downstream trough depends upon the zonal velocity according to the well-known Rossby formula. The zonal velocity in the western Pacific is such that the trough is usually located to the west of the islands in January and to the east in February (Namias and Mordy, 1952). Since the trough is characterized by convergence ahead and divergence behind, cyclones in Hawaii are more numerous in January than in February. The low rainfall in February is especially evident in the northern island of Kauai (Leopold and Stidd, 1949).

The easterly waves are trade-wind perturbations that may form during any part of the year but with a maximum during summer. In August the easterly waves occur along the east coast of Hawaii every 3 or 4 days, bringing with them decks of high clouds and rainfall; however, they dissipate readily over the rugged land and seldom reach Oahu and Kauai.

Since 1904 there have been only four tropical storms with wind of 74 mph or more passing through the islands, all in the 1950's. The formation of a hurricane in the central Pacific is somewhat of a climatic anomaly and requires a combination of favorable conditions. In 1957, when two hurricanes passed through Hawaii, Frazier (1957) noted that a well-developed

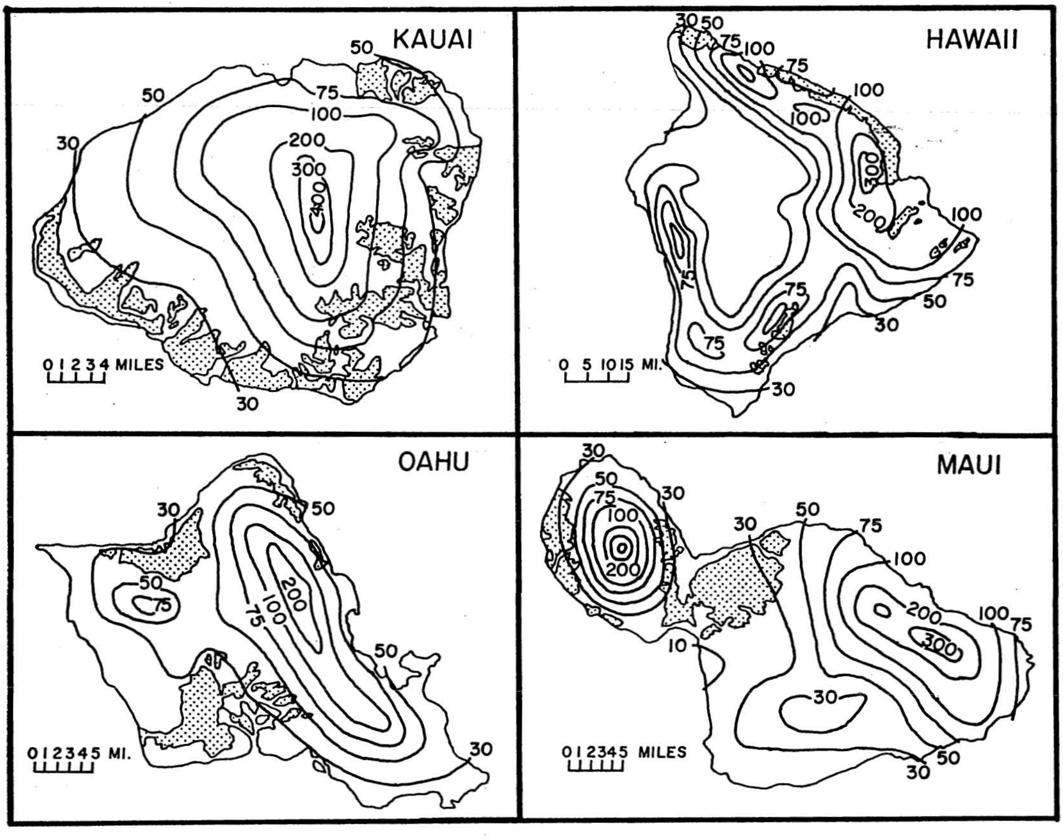

FIG. 4. Median annual rainfall (inches) in Hawaii.

trough extending to low latitudes persisted along the west coast of North America throughout the summer and fall season. This trough, through an energy dispersion mechanism, sharpens the next downstream subtropical trough, thus promoting cyclogenesis in the latter area (Ramage, 1959). The increase in radiation and temperature in Hawaii during the last decade, which will be discussed in a later section, was probably also an important cause for the increased hurricane activity.

RAINFALL

If the islands of Hawaii did not exist, the annual rainfall over the ocean would be in the neighborhood of 30 inches; the actual average rainfall over the islands is about 70 inches. This increase of 40 inches of rainfall is the result of orographic uplifting of trade wind and its perturbation-easterly waves. The effect of easterly waves is strongest near Hilo and diminishes northward toward the Hamakua coast. The median annual rainfall at Hilo is 139 inches, considerably higher than any other coastal area in the state (Fig. 4).

The trade-wind rainfall increases with altitude exponentially up to a certain point and then decreases again. The belt of maximum rainfall varies from 3,000 to 4,000 ft, depending upon the effect of local topography on the flow patterns. This effect has been discussed in detail by Leopold (1949). The steep isohyetal gradient in a trade-wind climate is best illustrated in Kauai, where Mt. Waialeale, with a mean annual rainfall of 465 inches, is only 15 miles away from the semiarid west coast. Most of the sugar plantations are located in lowlands with a median rainfall of less than 50 inches. A few cane-growing areas on Hawaii, however, receive as much as 200 inches of rainfall in a year.

Except along the Kona coast of Hawaii, where the upslope sea breeze produces frequent summer afternoon showers, winter is the wet season throughout the state. The contrast between summer and winter rainfall is most accentuated in the dry lowlands, where the monthly rainfall in summer is often less than 0.5 inch. Summer rainfall minima are found only in a very few places in the tropics and are designated as "As" climate in the Koppen classification.

In spite of the large areal and seasonal variations, the rainfall distribution for any particular month bears a close resemblance to that of the annual. Thus Stidd and Leopold (1951) were able to express the monthly rainfall as a function of annual rainfall in the following manner:

$$y = a\ (x - 30) + \mathrm{b}$$

where y is monthly rainfall; x, annual rainfall; a, the gradient factor of observed orographic increase of rainfall through increment of average annual rainfall; b, a geographic constant quantity derived from a rainfall blanket of uniform thickness over the islands and adjacent ocean. The constant 30 is inserted because the minimum annual rainfall in the dry lowland is about 30 inches.

This same concept was later expanded to describe daily rainfall distribution during trade-wind weather. For the island of Oahu, for example, a dry index of zero is assigned to a theoretical station having a zero mean annual rainfall, and a wet index of 100 to a station having 250 inches mean annual rainfall. A daily forecast chart is constructed by plotting the indices as the abscissa and the daily rainfall amounts as the ordinate. The forecaster forecasts the daily rainfall for the dry and wet index stations. From the straight line connecting these two reference points, daily rainfall for any actual station may be read off as the ordinate corresponding to the abscissa of the station's mean annual rainfall.

The trade-wind rainfall is more likely to occur during the night or in early morning than during the day. Loveridge (1924) attributed the nocturnal rainfall to the radiative cooling at the top of the clouds. Leopold (1948), however, added that cooling at night would lower the condensation level. Nocturnal rainfall, in distinct contrast to afternoon showers in many tropical countries, is in many ways beneficial to agriculture.

Trade-wind showers are very light, with drop size less than 2 mm in diameter (Blanchard, 1953), and with intensities usually much less than 0.2–0.3 inch per day. Only *kona* storms and hurricanes are capable of causing severe crop damage. On January 24, 1956, a *kona* storm deposited 38 inches of rain at Kilauea, Kauai. Such severe storms are rare, however, averaging

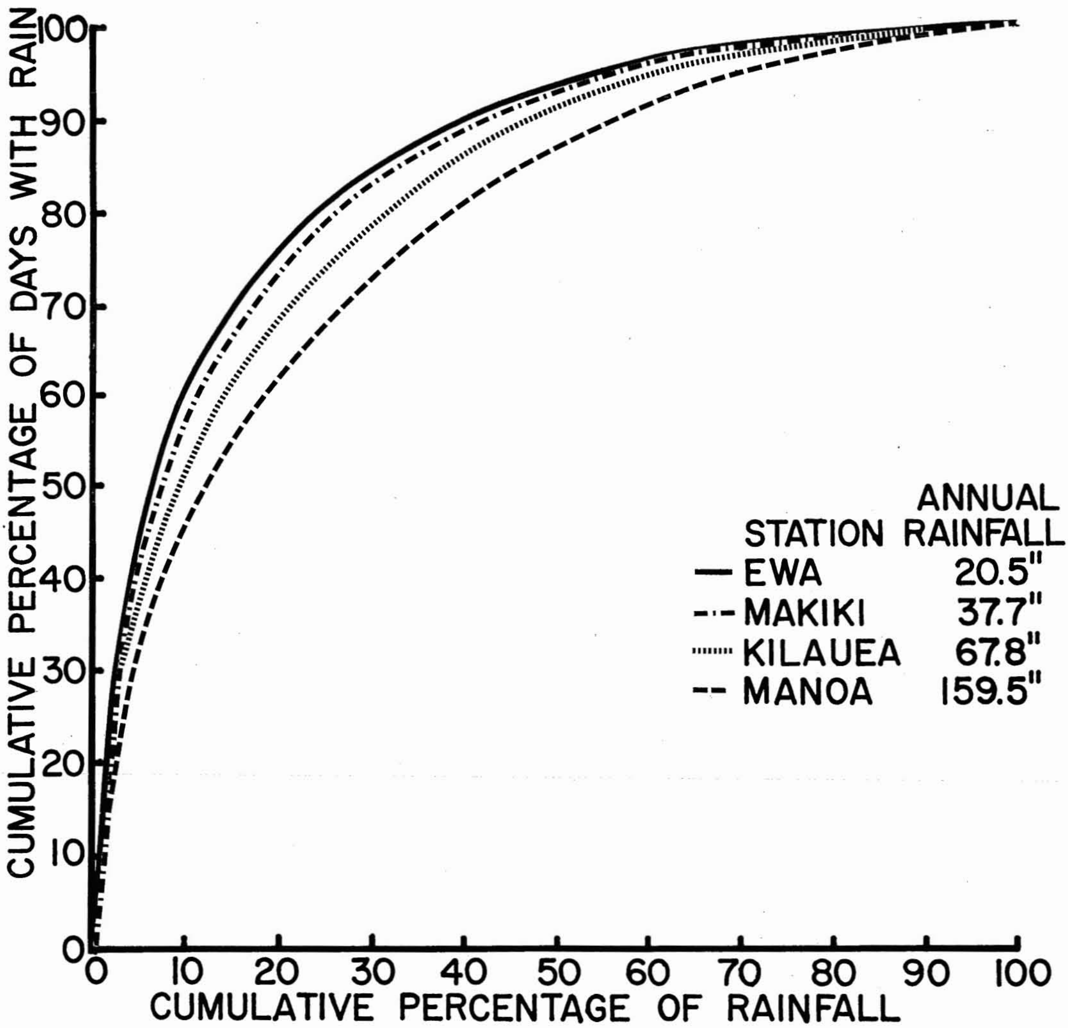

FIG. 5. Relationship between per cent of days with rain and per cent of total rainfall.

one in every 5 or 6 years. Furthermore, storm damages are usually restricted to Kauai and the east coast of Hawaii.

The frequency distribution of daily rainfall in Hawaii is extremely skewed. Figure 5 shows the relationship between the percentage of rainy days and the percentage of rainfall amounts cumulated from the least to the heaviest. At Ewa, for example, 10% of the days with the heaviest rain accounted for nearly 60% of the total, while 50% of days with least rainfall amounted to only 6% of the total rain. The skewness of the daily rainfall frequency curve decreases slightly with the increase of annual rainfall.

The skewed rainfall distribution has at least two important implications. First, a large amount of the annual rainfall will probably be lost as runoff. Second, the mean monthly rainfall will be considerably higher than the median, and the former is a poor indicator of the "normal" condition. For this reason median rainfall is used extensively in Hawaii.

As rainfall variability is very high in the tropics (Biel, 1929), even the use of the median is inadequate for many agricultural purposes. A knowledge of the extremes and frequency probabilities is indispensable. Because the basic cause of rainfall variation in Hawaii is rather uniform, the rainfall probabilities for different stations can be related in a simple, empirical manner (Landsberg, 1951). Figure 6 shows the probabilities (slanting lines) of having an annual amount of less than a given quantity (ordinate) as a function of the median annual amounts (abscissae), based on at least 60 years' records of 20 plantation stations. It is evident that Figure 6 could be used as a risk chart. Monthly rainfall probabilities could also be presented in the same manner.

TEMPERATURE

The mean annual temperatures in the lowland plantation areas vary from 72.5 F along the east coast of Hawaii to 75 F for the drier stations. The temperature decreases with elevation at an average rate of 4 F per 1,000 ft. The coldest plantation stations, at an elevation of about 3,000 ft, have a mean annual temperature of 62–63 F.

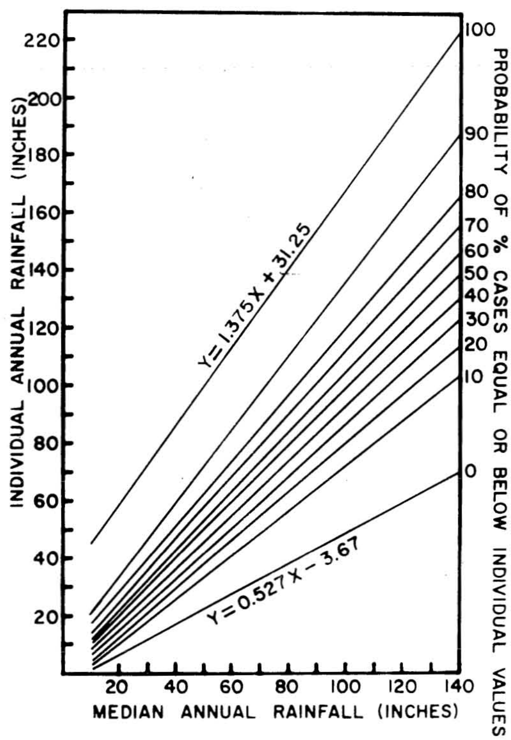

FIG. 6. Probabilities of having individual rainfall amounts in Hawaii as a function of median annual rainfall.

All the stations in Hawaii below an altitude of 5,000 ft have an annual temperature range of less than 9 F (Jones, 1942); thus a station at an elevation of 2,000 ft with an annual temperature of 65 F would have a minimum monthly temperature as high as 62 F. The isothermal climate is favorable for the growth of a perennial crop like sugar cane.

In Hawaii, as in many other tropical countries, the daily temperature range exceeds the annual mean daily temperature range and exhibits greater areal differences than does the mean annual temperature. Figure 7 shows the distribution of the annual mean daily temperature range in the cane-growing areas. In general the dry leeward stations have the greater temperature range. The daily temperature range is subject to a small seasonal variation, being slightly higher in the winter. According to the results of phytotron experiments at the California Institute of Technology, daily temperature range exerts a profound influence on fruit quality (Went, 1957).

The distribution of soil temperature in the tropics can be deduced fairly accurately from observations of air temperature (Chang, 1958). The mean annual soil temperature at any depth differs only slightly from the mean annual air temperatures. The annual temperature range at the soil surface under the cover of a sugar-cane crop is reduced to half of the air temperature range. Thus, in most of the lowlands in Hawaii soil temperature exceeds 72 F throughout the year. Studies at the Experiment Station have established that temperatures of 62 F are extremely limiting for cane growth and nutrient- and water-uptake. Such low temperatures are observed only in the mountains above 2,000 ft. The lowest soil temperature recorded on sugar cane land was 61 F at Hamakua plantation at an elevation of 3,000 ft.

RADIATION

Radiation measurements have been taken at 35 plantation stations by photochemical tubes which use oxalic acid as agent and uranyl sul-

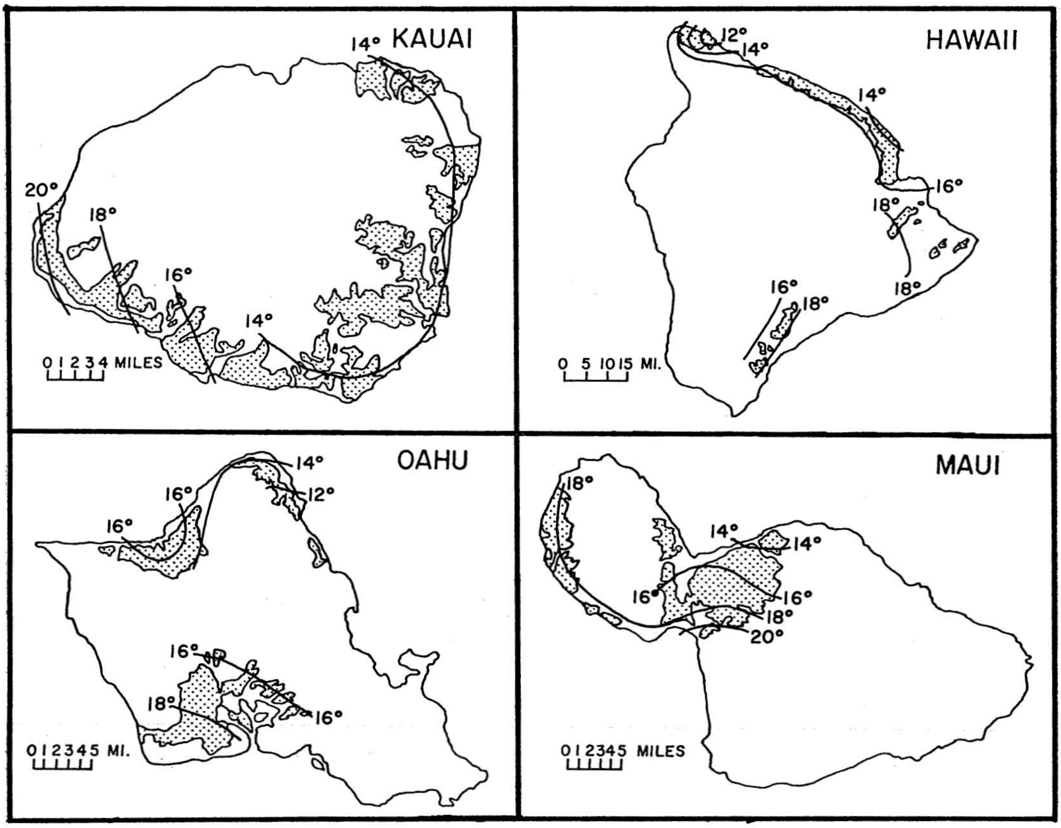

FIG. 7. Annual mean daily temperature range (°F) in Hawaii.

fate as catalyst. The photochemical method is accurate enough for general agricultural purposes (Chang, 1961). Apart from the direct effect on local climate and plant growth, the radiation data could be used for assessing yield potential, estimating irrigation water needs, directing fertilizer practices, etc. (Borden, 1940).

Figure 8 shows the distribution of mean daily radiation in Hawaiian sugar plantations. Maui has the highest radiation. Pukalani, in central Maui, receives 607 langleys/day or over 220,000 langleys/year. This is exceeded only by a very few desert areas in the world (Budyko, 1958). The average radiation for the cane-growing areas in Hawaii is in the neighborhood of 510 langleys/day, well above Houghton's (1954) estimate of 415 langleys/day for the land areas in the latitudinal zone 0°–20° N.

In Hawaii the minimum radiation is recorded in December, while the maximum is usually in June or July. The maximum monthly radiation is about 15% higher, and the minimum some 25% lower, than the annual mean. Radiation in December is about two-thirds that of June or July.

SECULAR CLIMATIC CHANGES

Since the cause for climatic variation in Hawaii is rather uniform, and since the leeward stations in particular are sensitive to circulation regimes (Landsberg, 1951), the climatic change at Makiki, in Honolulu, can be considered to illustrate that of the islands in general.

The average daily radiation at Makiki increased some 10% from 491 langleys/day in the 1930's to 544 langleys/day in the 1950's (Fig. 9). The rising trend probably started in 1936, but records before 1932 are not available.

Increased radiation results in a rise of temperature, though with a large time lag in a maritime climate. The temperature at Makiki (Fig. 10) did not start to rise until 1948.

Increased radiation could conceivably bring about a change in general circulation. Wentworth (1949) noted that the prevailing wind in Honolulu shifted from northeast to east from 1907 to the late 1930's and veered back thereafter. Increased frequency of east wind suggests a southerly location of the subtropical anticyclone, less frequent trade-wind weather, but not necessarily an increase in cyclonic activities; therefore, the trade-wind rainfall should decrease when the east wind is prevalent. At Makiki there was a trend to decreased rainfall from the 1920's to 1941 and to increased rainfall thereafter (Fig. 11). This explanation of the rainfall trend is tentative, however, and requires further study.

Whatever the causes for climatic change may be, its impact on agriculture is varied and profound. In general, the climate in Hawaii has become more favorable for sugar-cane culture during the last 20 years. This must account for part of the yield increase during that period.

MODIFICATION OF CLIMATE

The climate of Hawaii is, in general, well suited to the growth of sugar cane. Water economy is the one area where the climatic environment could be altered significantly to bring about a higher yield. Irrigation in the Hawaiian sugar industry started in 1852. At the present time 54% of the plantation area is irrigated. In

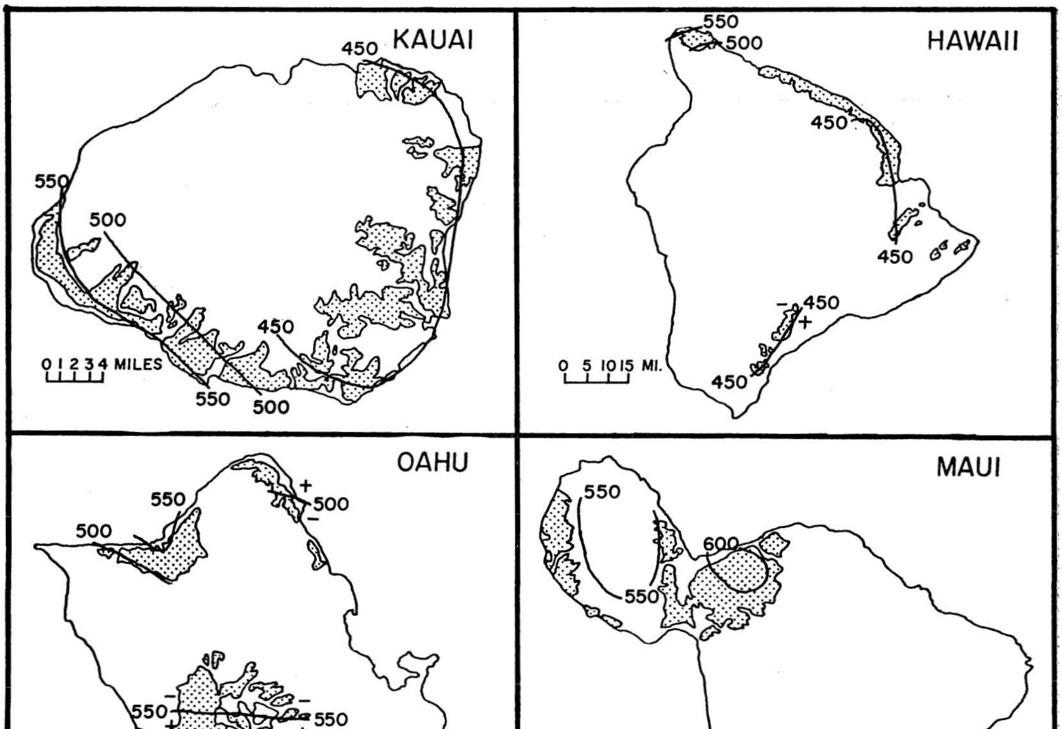

FIG. 8. Solar radiation (langleys/day) in Hawaii.

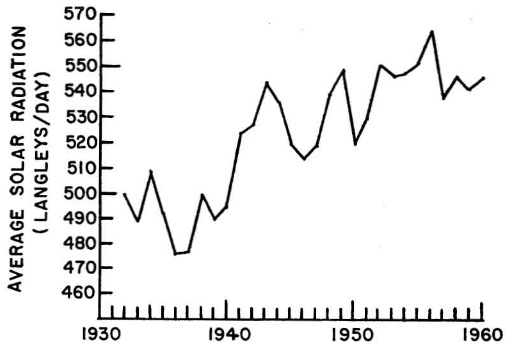

FIG. 9. Solar radiation at Makiki, 1932–60.

general the irrigated areas have less than 60 inches of rainfall in a year.

Intelligent management of irrigation requires a knowledge of the water need by a particular crop. Das (1936) advocated the use of day-degree as a measure of water need and as a guide to irrigation interval control. Numerous field experiments were conducted in Hawaii to determine the relationship between sugar yields and the number of day-degrees between irrigation. It was found that temperature is a poor indicator of the solar energy, which determines to a large extent the water needs of a crop. In fact, the monthly temperature and radiation at Makiki for the period 1932–60 have a correlation coefficient of only 0.57. The correlation is even poorer when the maximum temperature is used instead of the mean. In other parts of the world also, the use of day-degree as a phenological index has been refuted (Schneider, 1952; Wang, 1960).

As interest in the day-degree approach waned, Baver (1954) properly called attention to the rapid development of the evapotranspiration and other micrometeorological concepts and their application in irrigation. He contended that the meteorological approach has the advantage of simplicity of operation when compared with methods based upon measurement of soil moisture change. More important, however, are the many applications of evapotranspiration in determining the regional water balance and in disentangling the climate-yield relationship. With these ideas in mind the Experiment Station started an intensive study of micrometeorology in 1957.

EVAPOTRANSPIRATION AND ENERGY BUDGET

Sugar cane is a tall, ungainly plant with an aerodynamically rough canopy. Wind profile measurements indicate that the roughness parameter of a mature sugar cane of 4 cm height is 9 cm, as against 2.3 cm for thick grass of 10 cm height and 0.1 cm for short lawn grass (Sutton, 1953). The high roughness of a sugarcane crop renders the aerodynamic approach to evapotranspiration a difficult task (Deacon et al., 1958). This, together with the lack of a suitable instrument for measuring vapor flux, accounts for the fact that the aerodynamic method was not assayed in our experimental work.

The potential evapotranspiration of sugar cane was measured by drainage lysimeters and the data were analyzed by the IBM computer according to the Penman (1948) and Thornthwaite (1948) formulae. Detailed discussion of the instrumentation and the results has been reported elsewhere (Chang, 1961). It needs only to be emphasized that in a tropical mari-

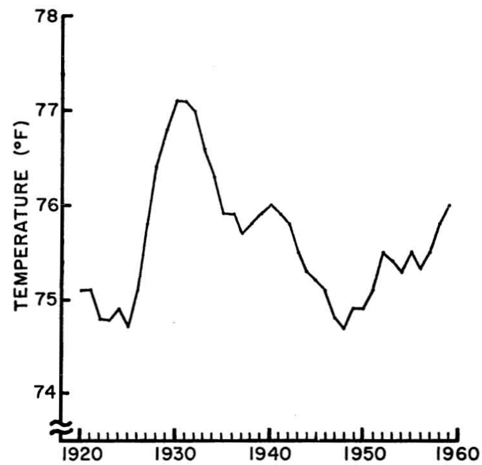

FIG. 10. Five-year moving mean of temperature at Makiki, recorded at middle year, for the period 1918–61.

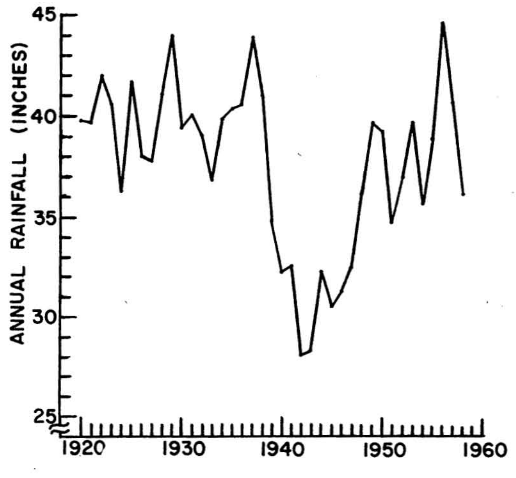

FIG. 11. Five-year moving mean of rainfall at Makiki, recorded at middle year, for the period 1920–58.

time climate the Penman estimates are far better than the Thornthwaite formula.

The various radiation components were measured at Makiki to evaluate the energy budget approach to evapotranspiration. Over a mature cane field the partition of incoming radiation is approximately as follows: 16% reflected radiation, 17% back radiation, and 67% net radiation (Fig. 12). The relationship between the net and incoming radiation is almost a constant throughout the year and over different vegetative surfaces. It was observed at Wahiawa that over short grass and pineapple fields, which have an albedo of about 5%, the net radiation remains two-thirds of incoming radiation. Theoretically it is difficult to reconcile the fact that the net radiation is not affected by the decrease of albedo, but from a practical standpoint this is convenient.

In the tropics, especially under the cover of tall vegetation, heat flux to and from the soil is negligible; therefore, the net radiation is consumed either in heating the air or in evapotranspiration. At Makiki 82% of the annual net radiation, or 55% of the incoming radiation, is used in evapotranspiration. There is a small seasonal variation of this percentage value, which is some 10% higher in summer than in winter.

There is also a regional variation of the energy partition. For instance, the percentage of insolation used in evapotranspiration increases with total radiation. In Hawaii the regional variations of energy budget are rather small, and the equation at Makiki could be used to estimate with reasonable accuracy the monthly potential evapotranspiration for other cane-growing areas in Hawaii. For estimating short term, say weekly, potential evapotranspiration it is advisable to use an evaporimeter which integrates not only radiation but other meteorological elements as well.

The simple energy budget presented here is applicable only in the humid tropics. In middle and high latitudes the energy budget is subject to enormous seasonal variations. In an arid climate the advective heat, which is extremely difficult to evaluate, may introduce a significant error.

PAN EVAPORATION AS A MEASURE OF EVAPOTRANSPIRATION

Until a cheap and readily installable piece of equipment capable of recording vertical vapor transfer is available, agricultural meteorologists will continue to use evaporation pans. In an arid climate pan evaporation is accentuated by the oasis effect to such an extent that its usefulness as a climatic parameter is greatly impaired. In humid climates, pan evaporation has been found to be more accurate than the Penman and Thornthwaite estimates (Suzuki and Fukuda, 1958), and a satisfactory guide to irrigation control (Krogman and Lutwick, 1961). In this

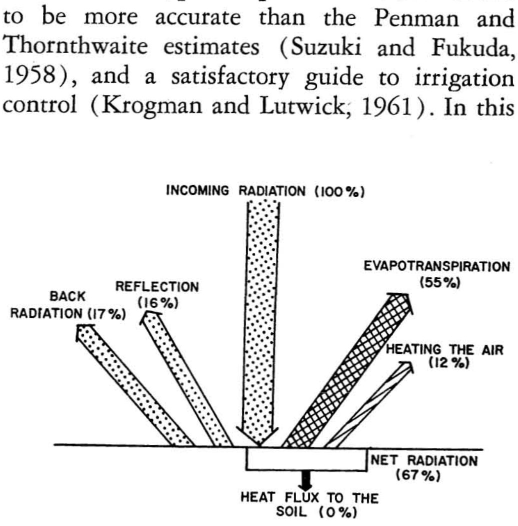

FIG. 12. Energy budget over a sugar-cane field at Makiki.

respect Hawaii is ideally suited to the use of evaporation pans, thanks to the existence of a moist mixing layer below the trade inversion.

Lysimeter and pan-evaporation records in Hawaii indicate that the potential evapotranspiration of mature sugar cane is approximately the same as evaporation from a ground-level U.S. Weather Bureau Class A pan. The ground-level pan, however, evaporates some 10% less than an elevated pan at cane top level, and some 15% more than a buried pan in an irrigated plot.

The one-to-one ratio obtained by using the ground-level pan is very much in line with ratios found for many other crops. From the standpoint of water use, crops may be divided into two groups: conventional and nonconventional. The potential evapotranspiration of a nonconventional crop is influenced to a large extent by its physiology. Rice, with a ratio of 1.2 (Suzuki and Fukuda, 1958), and pineapple, with a ratio of 0.35, are good examples. The water need of a conventional crop is determined primarily by the weather conditions, although it increases with the roughness of the crop, especially in areas of large advective heat (Tanner and Pelton, 1960). Thus the ratio increases from 0.75 for short grass (Penman, 1948) to 0.87 for corn (Fritschen, 1960*a*), and to 1.0 for sugar cane.

The fact that potential evapotranspiration of sugar cane approximates pan evaporation does not necessarily mean that irrigation based on a ratio of one-to-one is most economical. A new experiment has been set up at Waipio to determine sugar-cane growth and yield by using different pan ratios, i.e., 1.30, 1.15, 1.00, 0.85, 0.70, and 0.55. The yield data over a number of years should permit determination of the most economical level of irrigation.

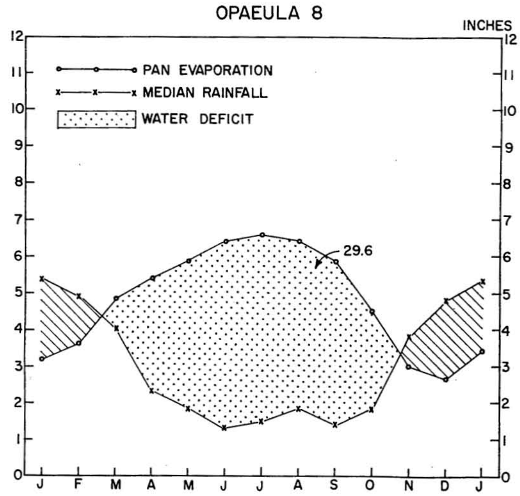

FIG. 13. Monthly water balance at Opaeula.

MONTHLY AND ANNUAL WATER BALANCE

The monthly water balance of a place can be portrayed by comparing the pan evaporation and the median rainfall. At Opaeula, for example, rainfall exceeds pan evaporation during the winter months from November to February (Fig. 13). From March to October, however, supplemental irrigation is needed to fill the water deficits, which total 29.6 inches in a year.

By analyzing the water balance of some 30 stations we have been able to construct an annual water-deficit map for the cane-growing areas in Hawaii (Fig. 14). The map is tentative, as the stations are not well distributed. Recently we have added 20 pan stations in order to strengthen the network. In constructing the map the radiation records were also used to fill the gap.

By planimetering the deficit areas in the map,

TABLE 1

ESTIMATED ANNUAL WATER DEFICIT FOR GROWTH OF SUGAR CANE

ISLAND	AREA (acre)	AVERAGE DEFICIT (inches)	TOTAL DEFICIT (acre-inches)
Hawaii	98,601	16.5	1,628,390
Maui	42,424	72.8	3,087,612
Oahu	33,223	41.0	1,361,141
Kauai	47,088	33.4	1,573,502
Total	221,336	34.6	7,650,645

the annual water deficits of the four islands are estimated as in Table 1. It is noted that there is a large regional variation. The average annual deficit for plantation areas on Hawaii, which are almost exclusively unirrigated, is only 16.5 inches. By contrast, the average deficit for Maui is as high as 72.8 inches.

The total annual water deficit for all the plantations is estimated at 7.6 million acre-inches, or 208 billion gallons. The industry uses about 400 billion gallons of water a year for irrigation. At first glance, the camp crop in Hawaii seems to be irrigated more than adequately. This is, however, not true. Much of the irrigation water is wasted due to maldistribution. For instance, a plantation irrigation at a high level of adequacy often loses as much as 60% of its water through deep penetration or runoff. Furthermore, the water supply is often such that a plantation over-irrigates in one season and suffers from drought in another.

The monthly water-balance charts and the water-deficit maps are a valuable guide to agricultural planning. Such questions as whether or not to construct a reservoir, what irrigation system to adopt, and what crop to grow can be answered, at least in part, through the use of climatic data.

The monthly water balance presented above is by no means precise because the median rainfall is only an approximation of the effective rainfall. The amount of effective rainfall varies with the rainfall intensity as well as with the moisture storage capacity of the soil. To credit rainfall correctly, it is necessary to compute the daily water balance.

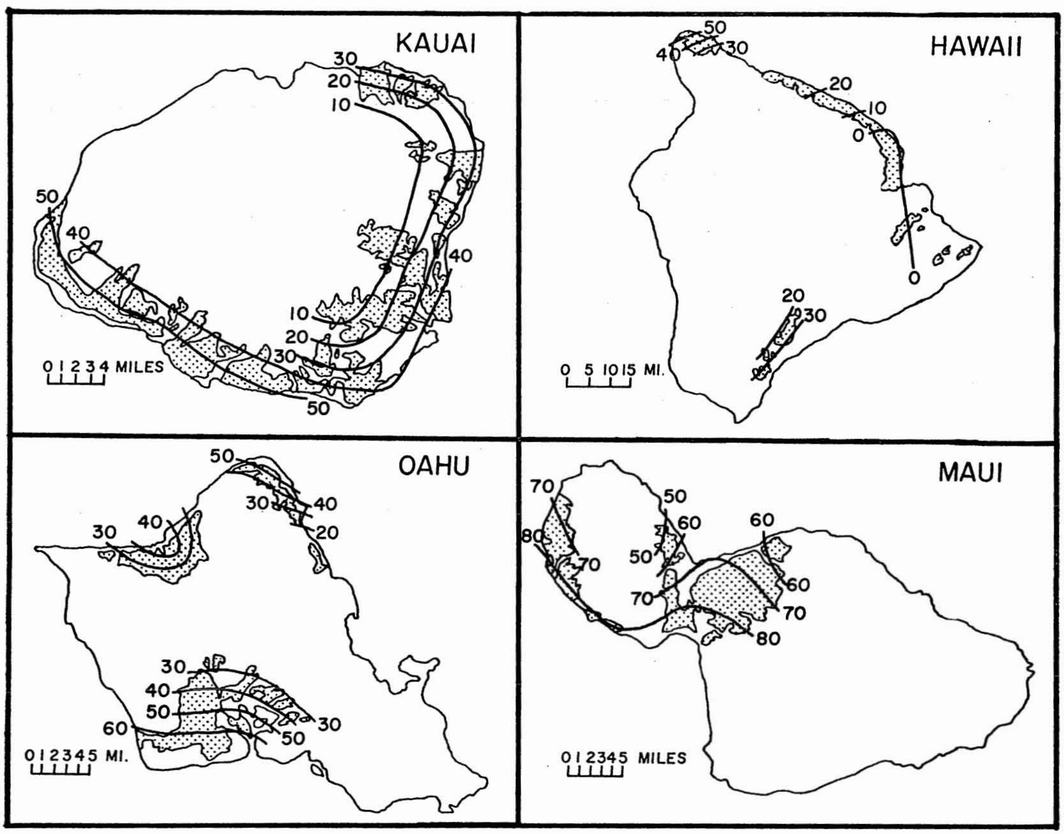

FIG. 14. Annual water deficit (inches) in Hawaii.

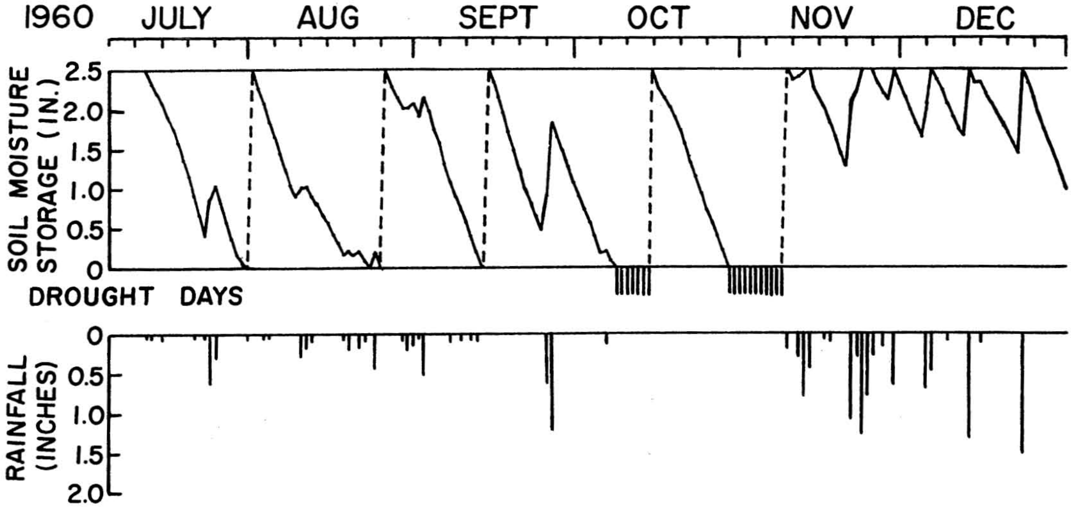

FIG. 15. Running daily soil-moisture balance at Waipio. Dashed lines indicate irrigation.

DAILY WATER BALANCE

If the soil storage capacity is known, the daily water balance can be computed by comparing the daily rainfall and potential evapotranspiration. Figure 15 shows the running daily soil moisture balance at Waipio, where the storage capacity is 2.5 inches. The rainfall in excess of the amount that a soil can hold is regarded as surplus. By subtracting the surplus from the rainfall, the effective rainfall can be determined. When the daily water balance reaches zero, drought occurs and irrigation is called for. The water deficits during the drought days can be added to determine the total water deficit during the growing season of a crop.

This daily water-balance scheme assumes that the depletion rate of soil moisture is equal to potential as long as the soil moisture is above the wilting point. This assumption is adopted primarily for simplicity of computation. It should not be taken to mean that we endorse the well-known Veihmeyer and Hendrickson argument (1955). Although the relationship between the depletion rate and the moisture tension is still debatable, there are indications that the relationship probably varies with weather conditions (Denmead, 1961). The constant depletion rate reported by Veihmeyer and Hendrickson is probably less in error in a humid, cloudy climate, especially under the cover of tall vegetation, than in a dry continental climate.

The computed daily water balance at Waipio has been compared with gypsum-block readings. They agree in general. When the water balance reaches zero, the gypsum-block resistance is usually between 3,000 and 5,000 ohms. The latter value calls for irrigation. In general, the irrigation date determined by the pan evaporation is one or two days earlier than that indicated by the block reading.

KOHALA RESULTS

Kohala is a plantation on northern Hawaii with an annual water deficit varying from 20 to more than 50 inches. In 1960 only about 27% of the plantation was irrigated. The question then arises as to whether an expanded irrigation program will be profitable in the long run. Apparently this question cannot be answered without an investigation of the climate-and-yield relationship.

The daily water balances during more than 10 years for one irrigated and five unirrigated stations in Kohala were computed by using a storage capacity of 3 inches. The total water deficits for different crops were summarized and correlated with the yields (Fig. 16). The correlations are highly significant for Hawi, Niulii 9, Halawa 3, and Upolu 6, but are poor for Puakea 6 and Union 8. In general they are very good for field crops, especially in view of the fact that there were considerable differences in crop age, solar radiation, cultural practice, variety, etc.

The average slope of the regression lines for the five unirrigated fields is 4.6 tons of cane per acre for every 10 inches of water. This is an important figure in determining the economy of irrigation. It is thought that by extending the regression lines to the point of zero deficit the approximate yield potential of the area could be estimated. The average yield for the five unirrigated fields was 65.2 tons of cane per acre. The estimated potential would be 91.4 tons cane per acre, or an increase of 40% over the present yield. This estimate is probably reasonable when compared with the yield of 109 tons of cane per acre at Waialua, Oahu, an irrigated plantation with slightly better climatic conditions.

Admittedly the use of linear extrapolation as a means of estimating yield potential is a crude procedure. Yet this seems to be the most reasonable method we can adopt at present. Theoretically the relationship between water and yield should be curvilinear, as shown in Figure 17. The exact shape of the curve cannot be determined until results of the Waipio experiments become available. The difference in yield potential between the two curves in Figure 17 is caused primarily by radiation, if soil and other factors are constant. Experiments are also underway to assess the effect of solar radiation on yield. It is hoped that in future this concerted research program will enable us to draw with certainty the climate-and-yield relationship now presented hypothetically in Figure 17.

By analyzing the daily water balance at Kohala, we also derived an empirical relationship between the actual rainfall and the effective rainfall for plant use. The computation was carried out by assuming varying soil-moisture storage capacities of 2, 3, and 4 inches. Figure 18 shows the curvilinear relationships between the annual rainfall and effective rainfall for all the five stations combined. Multiple regression analyses were carried out to the fourth power and a few selected values are given in Table 2. It is noted that the effective rainfall increases with the storage capacity only slightly, espe-

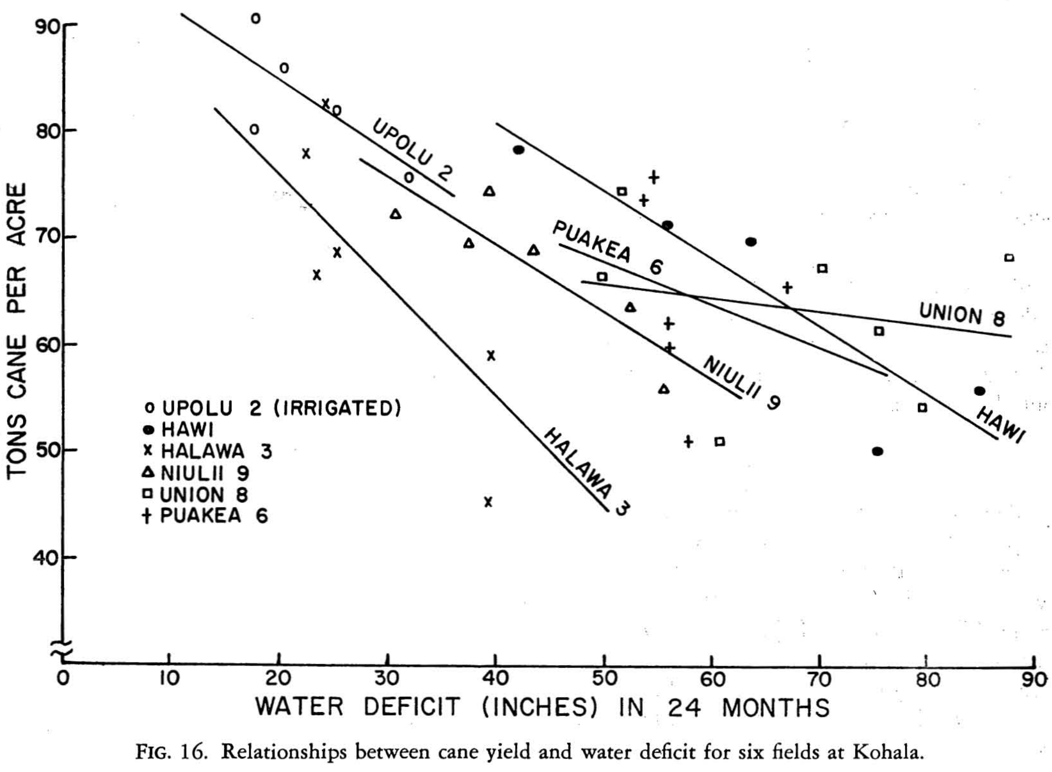

FIG. 16. Relationships between cane yield and water deficit for six fields at Kohala.

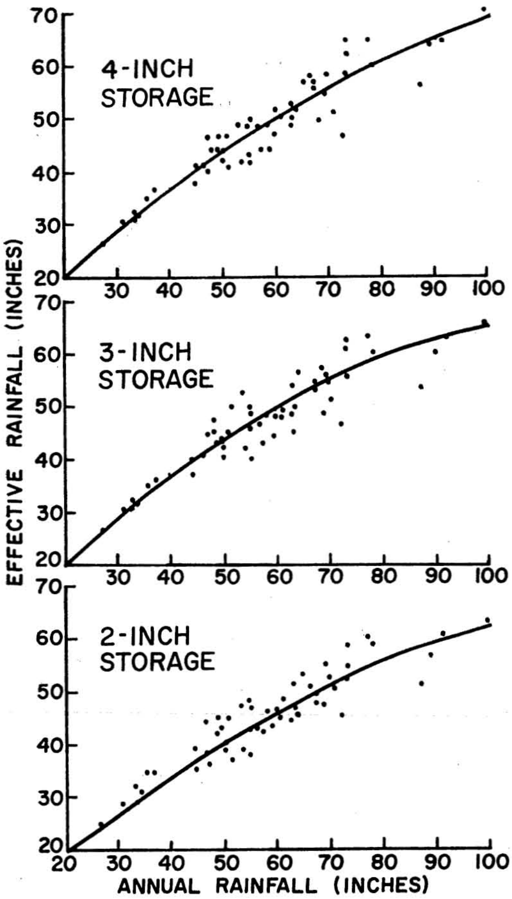

FIG. 17. Hypothetical curves showing the relationship between cane yield and climate in Hawaii.

cially when the annual rainfall is low. The Kohala results could be applied to other areas for estimating effective rainfall, as the rainfall characteristics are more or less similar throughout the islands.

JUICE QUALITY

The dry matter production of a sugar-cane crop can be related in a quantitative manner to the solar radiation and the amount of effective water applied, if cultural practices remain the same. The problem of juice quality is more complicated, however, and at present can be dealt with only in a rough empirical manner.

The weather factors that favor high sucrose content are:

1) High radiation favors photosynthesis and formation of sucrose.

2) Water supply should be adequate during the growing season, but should be followed by a dry period of about two months before harvest. High rainfall during the ripening period will dilute the juice and cause a part of the sucrose to break down into other sugars.

3) It is generally known that cool weather preceding the harvest season improves the sucrose content of the cane. Less well known, however, is the beneficial effect of large diurnal temperature range. Harrington (1923) and Morinaga (1926) have shown that alternating high and low temperatures hasten the germination of seeds and bulbs. If the buds of sugar cane react as favorably towards a great range of temperature, then earlier suckering could be expected, which would mean a greater number of mature stalks at harvest and hence a higher sucrose content.

In summary, the ideal weather for high juice quality would be abundant sunshine, high temperature range, adequate water supply during the growing season, and dry and cool weather during the ripening period. A study of Figures 7 and 8 would indicate that the Ewa, HC&S, Pioneer Mill, and Kekaha plantations have the best climate for good juice quality.

It is true that we cannot modify the climate to such an extent as to appreciably improve the juice quality. Nevertheless, an understanding of

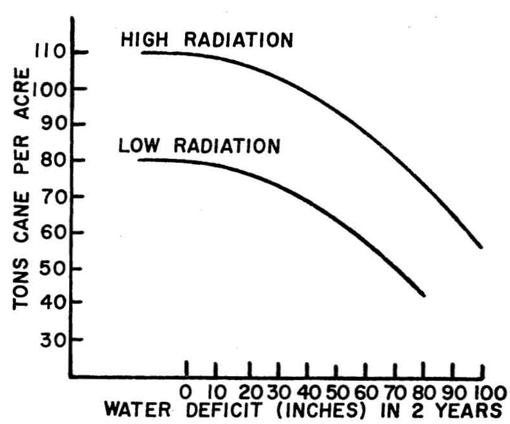

FIG. 18. Relationships between annual rainfall and effective rainfall in Kohala, assuming varying soil-moisture storage capacities of 2, 3, and 4 inches.

TABLE 2

EFFECTIVE RAINFALL AS A FUNCTION OF ANNUAL RAINFALL AT KOHALA
(Assuming varying soil moisture storage capacities of 2, 3, and 4 inches)

Annual rainfall (inches)	40	50	60	70	80	90	100
Effective rainfall for:							
2-inch storage	34	40	46	52	56	60	61
3-inch storage	37	43	49	55	58	62	65
4-inch storage	37	44	50	56	60	65	69

the climatic effect on juice quality has at least two practical applications. First, we can schedule planting and harvest dates accordingly, in order to best fit the seasonality of a climate; in this connection a study of climatic singularity would be valuable. Second, an understanding of the role played by climate could help us to interpret the results from many agronomic experiments.

CONCLUDING REMARKS ON CLIMATOLOGICAL RESEARCH

This review has demonstrated the broad scope of climatological research in the Hawaiian sugar industry. The application of this research, as Curry (1952) pointed out 10 years ago, could ultimately give new life to many an economic activity. Toward that end we have made only a beginning. Much work remains to be done. Future research should be planned in three general areas:

1. GENETIC CLIMATOLOGY: Only 20 years ago climatology was treated primarily as a study of statistical meteorology, replete with records but almost devoid of explanations. The post-war studies of the climate of Hawaii are among the pioneers in the field of genetic climatology. These studies bring a fair measure of systematic order into the otherwise incoherent climatic facts and explain many seemingly local phenomena in the light of general circulation. A better understanding of the dynamism and genesis of climate could conceivably lessen or avert agricultural hazards in many other parts of the world. It is hoped that Trewartha's new book (1961) will stimulate interest and hasten development in this field.

2. ENERGY BUDGET AND WATER BALANCE: Genetic climatology focuses its attention on the free atmosphere. Local variations, caused by the interaction of the atmosphere and the terrain, can best be understood by a study of the energy budget and water balance. Conventional observations, tied to the needs of synoptic forecasting, are often inadequate for the study of topoclimate. Urgently needed is an internationally-standard field instrument for the measurement of solar radiation. The recent development of an instrument which measures net radiation (Soumi et al., 1954; Fritschen, 1960*b*), or even net radiation minus soil heat flow (Portman, 1954), is most encouraging.

Measurements of evapotranspiration by inexpensive field instruments are also needed on a wider scale. In humid climates evaporimeters, such as evaporation pans or atmometers (Halkais et al., 1955), have been of value. In arid climates, however, the problem is vexing. There the very concept of potential evapotranspiration is elusive and unrealistic. For potential evapotranspiration requires, by definition, a homogeneous soil moisture regime infinite in horizontal extent, and once the area upwind is adequately watered the climate is no longer arid. In actuality the effect of advective heat exists even in a very large irrigated area. Gal'tsov (1953), for instance, has observed decreasing water requirements from the border towards the center of an irrigated region in Kazakhstan. It is difficult to evaluate the effect of advective heat. Perhaps an approach similar to but more refined than Belasco's study (1952) on the modification of air mass is in order.

To solve the water-balance equation the soil moisture storage capacity needs to be known. This requires the cooperation of soil scientists. On a global scale, representative figures of moisture storage capacity of the major geographical regions are useful for many purposes.

In view of the importance of energy budget and water balance in characterizing the regional climate, it is a pity that almost all the textbooks in English on climatology make no reference to the subjects. The Russian work by Budyko (1958) is the only general reference. In this respect, Thornthwaite's sustained interest in these areas is commendable, and his recent plea (1961) should be well heeded.

3. EFFECT OF CLIMATE ON GROWTH AND YIELD: We have demonstrated that determination of water balance is a step toward solving the climate-and-plant relationship. More field experiments are needed, however, to define the hypothetical curve as presented in Figure 17. Eventually we hope that a method will be developed to estimate dry-matter yield and juice quality from climatic data.

It has been argued that climatologists are not responsible for the study of the effects of climate on vegetation (Trewartha, 1957). To be sure, plant scientists are better qualified to run the field experiments. But the development of techniques for evaluating the climatic elements that affect plant growth falls squarely within the responsibility of a climatologist. Without these techniques the meaning of climatic data is often obscured. Whoever solves the problem of climate-and-plant relationship will contribute work of enormous practical value.

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