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AN ESTIMATE OF PALEOCLIMATE IN OAHU, HAWAII*

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ABSTRACT. The present isohyetal pattern is related mathematically to the present topographic and orographic surface of Oahu, Hawaii. Geologic evidence shows that during the past sealevel stood higher and lower on the island than at present. An estimate of paleoclimates can be made by determining the mathematical fit of the present isohyetal pattern to the present topographic surface, varying the topographic surface for past high and low sea stands, and calculating paleo-isohyetal patterns for each case.

INTRODUCTION

Climatologic considerations.—The present climate of the Hawaiian Islands reflects the classic influence of orographic-convection cells (Riehl, 1954, p. 111-114). Outstanding features are differences in rainfall in adjacent areas, equable temperatures devoid of marked seasonal changes, and the persistence of trade winds. Two primary determinants of climate are location in the trade-wind belt and topographic forms of the islands (Leopold, 1951, p. 1). Wind direction determines what proportion of horizontal flow will be converted into vertical orographic-convective motion; wind speed determines the rate of moisture flow which directly affects the rainfall intensity; and the height of the trade-wind inversion determines the available supply of moisture (Solot, 1950, p. 36). Rainfall is a function of the water content of the air and the rate of ascent of the air up topographic slopes (Riehl, 1954, p. 112). Local climatic changes are influenced by size and trend of mountains and valleys, nearness or remoteness from the sea, and direction from the sea relative to the trades (Feldwisch, 1941; Blumenstock, 1961). Flow patterns are complicated by local sea-land and mountain-valley wind regimes which interact with the general trade-wind flow and which develop cloud and precipitation patterns that affect local temperature, humidity, and rainfall (Leopold, 1949, p. 312).

The annual rainfall over the Hawaiian Islands increases inland from the coasts so that if isohyets are spaced in geometric progression, the distance between them becomes nearly uniform (Leopold, 1951, p. 2; Riehl, 1954, p. 111). Rainfall increases rapidly from the coastlines to the mountain tops, and maximum rainfall is just lee of the summit line where crests are less than 5000 feet in elevation (Leopold, 1951, p. 1). On mountains whose summits penetrate the trade-wind inversion at approximately 7000 feet, maximum rainfall is near 3000 to 4000 feet, and the higher lying summits are more arid (p. 2). On the island of Oahu the crests of the Koolau and Waianae Ranges are well below the base of the inversion layer, and as will be shown later, even with Pleistocene eustatic changes in sealevel that relatively raised and lowered the summits, the mountain tops never penetrated the tradewind inversion. On Oahu a Lanai-Molokai type circulation pattern is dominant (Leopold, 1949, p. 312-316). Trade winds flow over the low mountain barrier and are opposed on the lee side by onshore sea breezes. They meet in a narrow zone where there

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* Contribution of Soil Survey Investigations, Soil Conservation Service, U. S. Department of Agriculture.

must be vertically rising air. A long cloud line lies approximately directly over the sea-breeze front and parallel to it. On either side are zones of subsidence with two long cells of circulation which have parallel horizontal axes. Convective rainfall from the cloud line provides a distinctive closed isohyetal pattern on the mean rainfall map (p. 316).

Rainfall in Hawaii has also been related to three basic atmospheric flow patterns which are precipitation from (1) trade winds, (2) extratropical cyclonic disturbances such as polar troughs and frontal passages, and (3) cyclonic situations such as easterly waves (Solot, 1950, p. 36; Yeh, Wallen, and Carson, 1951, p. 35). Although the latitudinal extent of the Hawaiian Islands is small, they lie in the critical boundary zone between atmospheric circulation zones of high and low latitudes (Solot, 1950, p. 8). Seasonal maxima of rainfall differ from the island of Hawaii to Kauai and coincide with northward retreat of the westerlies and corresponding advance of the easterlies. As the easterlies advance northward, rainfall maxima shift from Hawaii to Kauai (p. 8). Oahu is between the other two islands. Rainfall on Oahu also appears to be related to the latitudinal centering of the circumpolar westerlies. As the jet stream centers more than 20° north of the island, rainfall in winter generally increases, and when the westerlies center south of this latitude, rainfall decreases (Yeh, Carson, and Marciano, 1951, p. 51).

However, orographic rain from trade-wind circulation is dominant throughout the year and so greatly dominant that any correlation between cyclonic disturbances and rainfall is negligible (Yeh, Wallen, and Carson, 1951, p. 36, 38). Even increased precipitation in winter on Oahu is due as much to the increase in intensity and frequency of trade-wind rain as it is to the increased frequency of cyclonic rain (p. 41).

The orographic effect on rainfall at a station on Oahu should be, in part, a function of wind direction, and in general, a south wind is associated with heavier rainfall than a north wind, but there is little difference between west and east winds (p. 43, 44). However, a series of monthly median rainfall maps of Oahu shows each month's pattern closely resembles every other month's pattern and, in turn, the mean annual pattern (Stidd and Leopold, 1951, p. 25). Further, the similarity of patterns between winter and summer months is so great that only slight differences are detected even in careful analysis. The similarity of patterns is attributable to the orographic rain from trade winds on Oahu which localizes centers that serve as focal points for rainfall activity; orographic rainfall invariably starts and maintains strongest activity at these focal points regardless of wind direction or other synoptic considerations (p. 28, 30). Correspondingly, in any cases of marked variability of rainfall, the whole island of Oahu is uniformly affected (Landsberg, 1951, p. 18).

Thus, the dynamic situation of present climate on Oahu is an orographic-convective cell producing localized, intensive rainfall centers from trade winds near mountain summits which serve as focal points for rainfall activity regardless of wind direction. Orographic rain from trade winds dominates precipitation from other synoptic situations in all seasons of the year and yields a rainfall pattern similar in kind throughout the year.

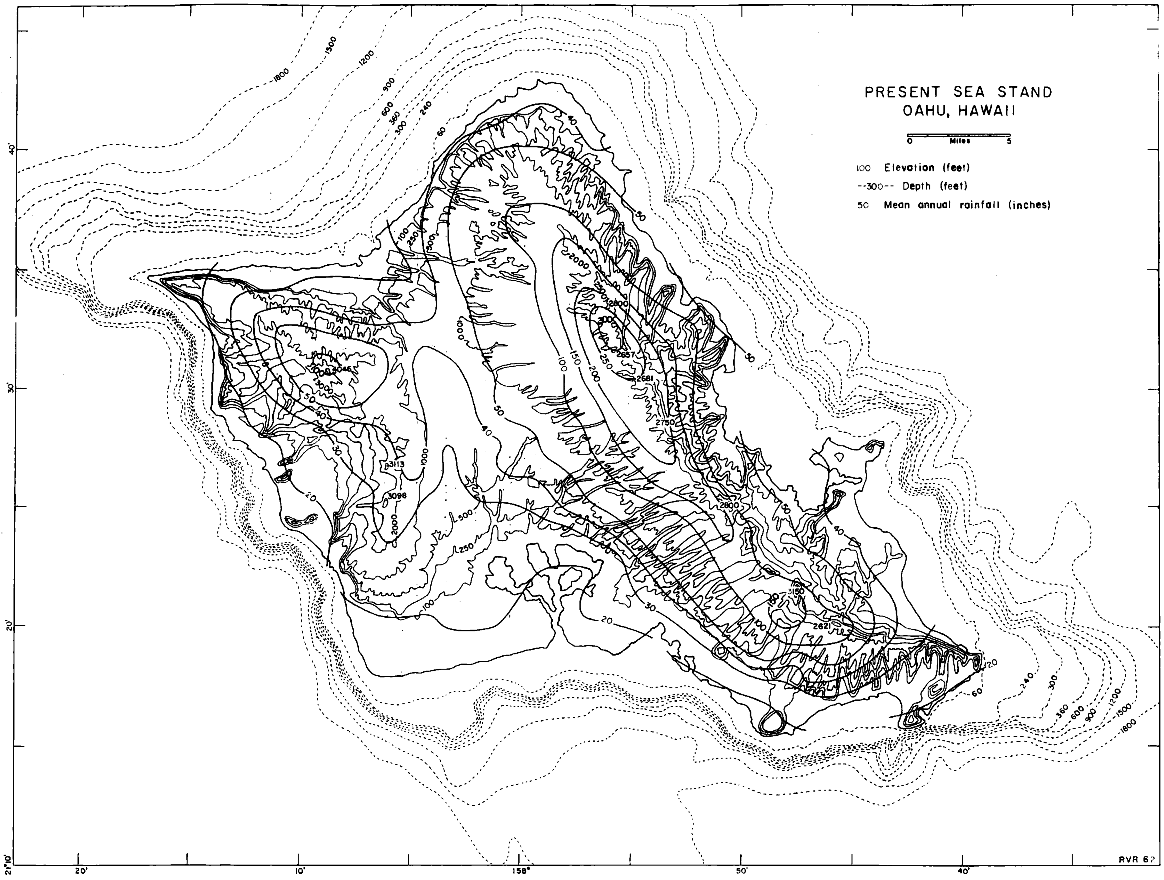

Fig. 1. Relationship of present isohyets to topography, Oahu, Hawaii.

If an estimate is to be made of past climates of Oahu, an examination of possible past radical changes in atmospheric circulation is necessary. The existing planetary circulation over the oceans in tropical and subtropical regions is generally explained as a simple meridional circulation cell (Riehl, 1962, p. 13-14). Observations during the past few decades, however, have thrown doubt on such a simple view and apparently are initial attempts to establish the processes of the tropical general circulation (p. 13, 22).

Estimates of planetary circulation over the oceans during the geologic past have been based on the concept of the meridional circulation cell. As circulation is a result of zonal temperature differences poleward from the equator and the rotation of the earth, an equatorial low pressure belt, trade winds, and subtropical anticyclones should have existed in the past (Brooks, 1949, p. 55). During glacial maxima in contrast to the present, theoretical main features were an intensified circulation with a general displacement toward lower latitudes of the present zonal pattern (Willett, 1949a, p. 43; 1949b, p. 300; 1950, p. 180-182; 1953, p. 54-55; Brooks, 1949, p. 59; Lamb, 1961, p. 39) that resulted in a narrow belt of strong trade winds at low latitudes (Brooks, 1949, p. 59; Willett, 1950, p. 181; Lamb, 1961, p. 39).

Supposedly a subtropical high pressure belt, an east-west orientation of elongated Atlantic and Pacific cells, centered 5 to 10 degrees nearer the equator than at present, and with correspondingly low pressure at the equator caused strong, steady easterly trade winds (Willett, 1950, p. 181). However, Simpson (1934, p. 438, 439, 463) concluded from his reconstructions of past patterns that there were no radical changes in pressure distribution or direction of prevailing winds over the Pacific Ocean during the glacial maxima. Schell (1949, p. 225) pointed out that the present circulation in the North Atlantic shows no tendency to act in unison with the circulation in the North Pacific so there would be no reason to expect similarity of pattern in the past. Schell (1961, p. 257, 264-265) further pointed out that there was little cooling over the North Pacific in glacial time. Hence poleward temperature gradients and presumably dependent circulation patterns would be little different from the present.

During interglacial times in contrast to the present, the theoretical main features of the climatic pattern and atmospheric circulation were a displacement of the zonal pattern toward the poles accompanied by a less intensified circulation (Willett, 1953, p. 55). On the other hand, there is the opinion that the circulation over the Pacific was not unlike that of today.

In attempting to estimate past climates on Oahu, it would be difficult to quantify the theoretical speculations regarding atmospheric circulation at times of glacial and interglacial maxima. The island undoubtedly was in the tradewind zone during both times. From one point of view, winds may have been stronger and more easterly during glacial maxima and weaker and more northerly during interglacial time. From another point of view, winds may have been similar to the present conditions. Correspondingly as a point of departure for estimating past climate, it seems best to use the present synoptic situation of Oahu with the assumption that "The present pattern . . . of atmospheric circulation lies somewhere between the extreme of a maximum of of glaciation and the extreme of an interglacial minimum . . . " (Willett, 1953,

p. 54). The present regimen on Oahu is assumed to be somewhat like past glacial and interglacial times.

Divergent conclusions also can be drawn from inferred climatic records of deep sea cores. In a series of cores from 4° S to 17° N lat between 120° and 130° W long, 2600 to 2700 miles southeast of Hawaii, nine warm and nine cold stages were recognized in the Pleistocene section (Arrhenius, 1952). Climatic stages were interpreted from variations in carbonate content in the cores, that is, high carbonate content corresponded to low water temperature and related atmospheric conditions. A chronology based on the rate of accumulation of TiO_2 was established for the cores and involved the assumption that the rate of accumulation of TiO_2 remained constant during the time represented by the cores. The rate was calibrated by one radiocarbon date at the base of one core. Computations were then made of the relative rate of low latitude atmospheric circulation during the Pleistocene, estimated from the rate of accumulation of biogenous solids below the equatorial current system in the Pacific (Arrhenius, 1959, p. 127). Calculated equatorial rates (intensities) of circulation in the Pacific during glacial times were 2 to 3 times the rates for the present and also for interglacial times.

Although agreeing with the correlation between high carbonate stages in cores and low general temperature, Emiliani (1955, p. 561) concluded from oxygen-isotope analysis of the same cores that temperature variations in the Pacific cores are far less conspicuous than in cores from comparable latitudes in the Atlantic Ocean. Isotopic temperatures from benthonic Foraminifera in the cores showed that bottom temperatures of glacial ages were the same as today, and interglacial bottom temperatures were not more than 0.8°C higher than today (p. 564). The temperature decreased about 3°C from late Pliocene to the Pleistocene but oscillated about 3°C in amplitude during the Pleistocene. The oscillations do not provide a clear temperature record for the Pleistocene because of local pattern of vertical circulation of surface water, because only species of deeper habitats were available for isotopic analysis, and because the amplitude of the temperature variation was small (Emiliani, 1961, p. 526). Accordingly, the oscillations may be interpreted in terms of climatic changes, but the exact relationships are not clear.

As in the case of theoretical climatic considerations, conclusions about climatic change based on deep-sea cores are not diagnostic. On the one hand, change appears to be indicated, but on the other hand, similarity is shown. Consequently, as in the case of theoretical considerations, it seems best to use the present synoptic situation of Oahu as a point of departure for estimating past climates. There is no absolute evidence to show a radical change in wind direction or intensity. Direction is of lesser importance as analyses of present rainfall patterns have indicated. Each month's pattern resembles every other month's pattern; each season's pattern resembles every other season's pattern; and all patterns resemble the mean annual pattern. For example, at Honolulu monthly median wind directions vary from N 74° E in January to N 51° E in May, a shift of 23°. Summer median direction is N 53° E and winter median direction is N 63° E, a shift of 10°. Annual median direction is N 55° E.

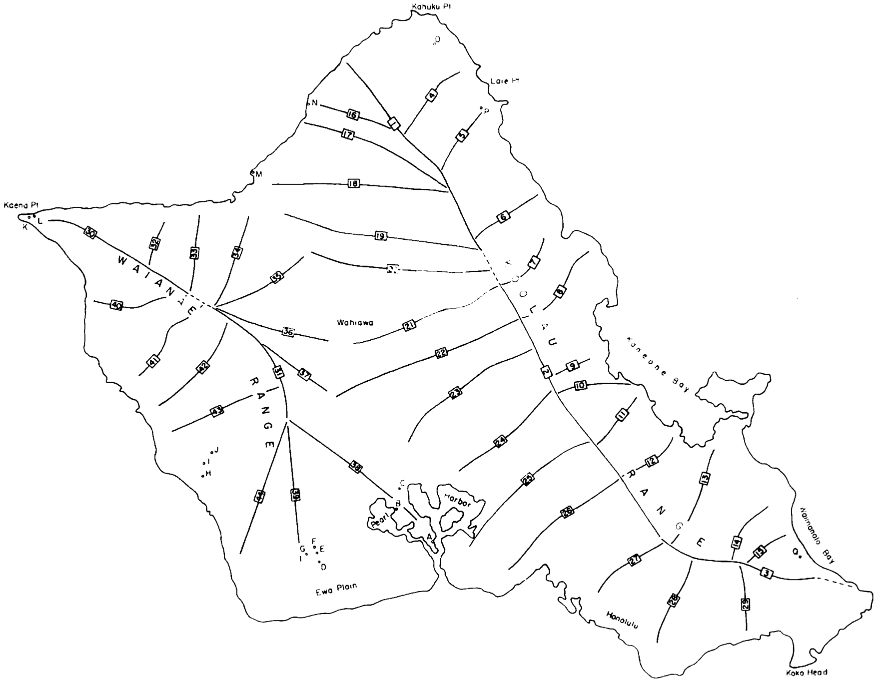

Fig. 2. Network of traverses along summit axes of mountain ranges and to windward and leeward of summit axes for calculating fit of isohyetal to topographic surfaces.

Marked change in wind speed conceivably would affect rainfall intensity as the speed determines the rate of moisture flow to the orographic-convective cell. However, absolute values cannot be placed on wind intensity for the past, but qualitative corrections for increased intensities can be applied in the calculations that follow in this paper.

Geologic considerations.—There is considerable evidence and reasonable agreement among geologists that sealevel during past times was higher and at other times lower than present in the Hawaiian Islands (Wentworth and Palmer, 1925; Stearns, 1935a, b; Stearns and Vaksik, 1935). Stearns (1961) summarized and further elaborated upon his earlier studies and recognized 14 "ancient" shorelines above present sealevel and 5 below it. Many of these levels were questioned previously (Russell, 1963), and field studies on Oahu with colleagues[1] during the past 3 years and progressing currently have failed to verify existence of some levels. In addition, detailed statistical morphometric analyses of profiles of shorelines and submarine shelves fail to record occurrence of some levels. However, both field and morphometric studies show distinct subaerial levels at Stearns' (1961) Waimanalo and Kaena shorelines, 25 and 95 feet above sealevel respectively, and a possible level of 10 to 15 feet above sealevel—the Hanauma shoreline of Wentworth and Palmer (fig. 2.

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[1] J. M. Williams and E. L. Hill, Soil Conservation Service, U. S. Department of Agriculture, Honolulu, Hawaii; results to be published elsewhere.

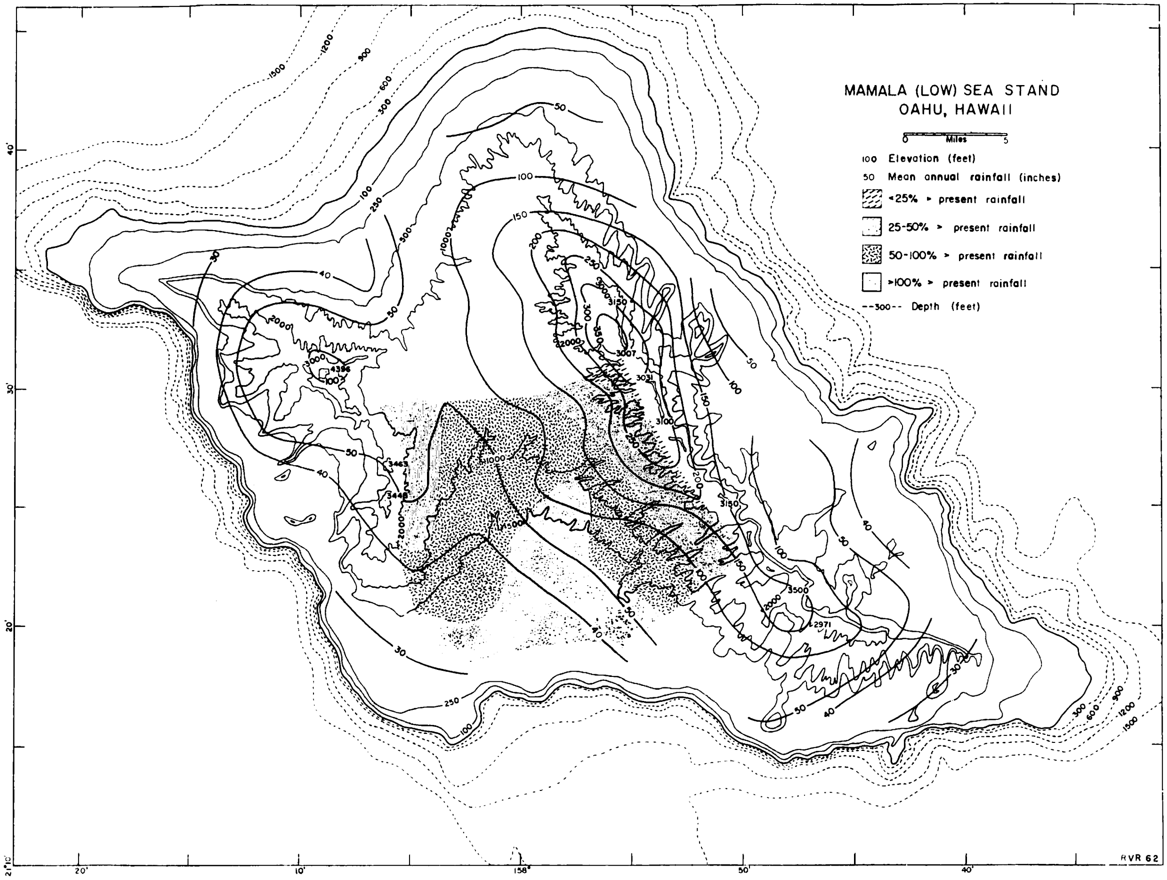

Fig. 3. Relationship of isohyets to topography during Mamala, −350 foot, sea stand, Oahu, Hawaii. Shaded areas compare rainfall of Mamala time to present.

A-Q). The Waimanalo stand is supposedly Sangamon in age and the Kaena late Yarmouth (Stearns, 1961).

A shelf descends gradually from the present shoreline of Oahu around the island to a depth of approximately 350 feet where the gradient changes abruptly and descends steeply to a lower major submarine shelf or to abyssal depths. Arithmetic mean depth of the break in gradient calculated from 182 bathymetric profiles[2] is 57.6 fathoms or 345.6 feet with a standard deviation of 9.6 fathoms or 57.7 feet and a probability of >99.9 percent. This rounded value of minus 350 feet modifies Stearns' (1961) "Tazewell [sea] stand of minus 300± feet". More than coincidentally, the calculated morphometric values are in excellent agreement with one recent calculation of sealevel lowering due to growth of continental ice sheets in classical Wisconsin time of 58 fathoms or 348 feet (Donn, Farrand, and Ewing, 1962). The minus 350-foot submarine shelf is here named the Mamala shelf after Mamala Bay off the mouth of Pearl Harbor.

Assignment of the valid subaerial and submarine levels to glacio-eustatic stands of the sea has been questioned (Shepard, 1961). However, specific levels such as –350, +25, and +95 feet *per se* are not in question but rather the cause of their elevation or depression, that is, whether glacio-eustatic or tectonic.

If two of these former sea stands, –350 feet and +95 feet and the latter rounded to +100 feet, are accepted as valid, then topographic surfaces of Oahu can be reconstructed for these levels. The Kaena and the Mamala shorelines postdate the formation of the major topographic features of Oahu. Remnants of the Kaena level—coral limestone, beach deposits, wave cut scarps, and niches—occur around the island on the lower slopes of mountains where they descend abruptly to the sea and also at the southern and northern seaward margins of the Wahiawa Basin between the Koolau and Waianae Ranges. In these areas the Kaena scarp is cut into the lowest level of a stepped sequence of surfaces that rises in the basin and up the west and east slopes of the respective mountain ranges. The mountain slopes and summits and the major features of the Wahiawa Basin were all formed prior to the Kaena stand of the sea. Similarly the major features of the island were formed before the Mamala shoreline which is presently 350 feet below sealevel.

Since the present isohyetal pattern can be fitted mathematically to the present topographic surface, paleo-isohyetal patterns can be calculated from the reconstructed topographic surfaces of the two selected sea stands. Points on the island were elevated 350 feet in the case of lowered sealevel. In the case of raised sealevel, points on the island were lowered 100 feet (figs. 3, 4). In the case of lowered sealevel the area of the island was increased. A broad coastal plain of low gradient rose gradually from sealevel to the base of the mountain ranges where slopes ascended steeply to the relatively higher summits (fig. 3). In the case of raised sealevel, slopes rose steeply from the shoreline to relatively lower summits (fig. 4). The problem in estimating the paleo-isohyetal patterns involves relating the present isohyetal pattern to the present topographic

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[2] From U. S. Coast and Geodetic Survey Chart 4110, Island of Oahu, scale 1:80,000, 7th ed., 1961.

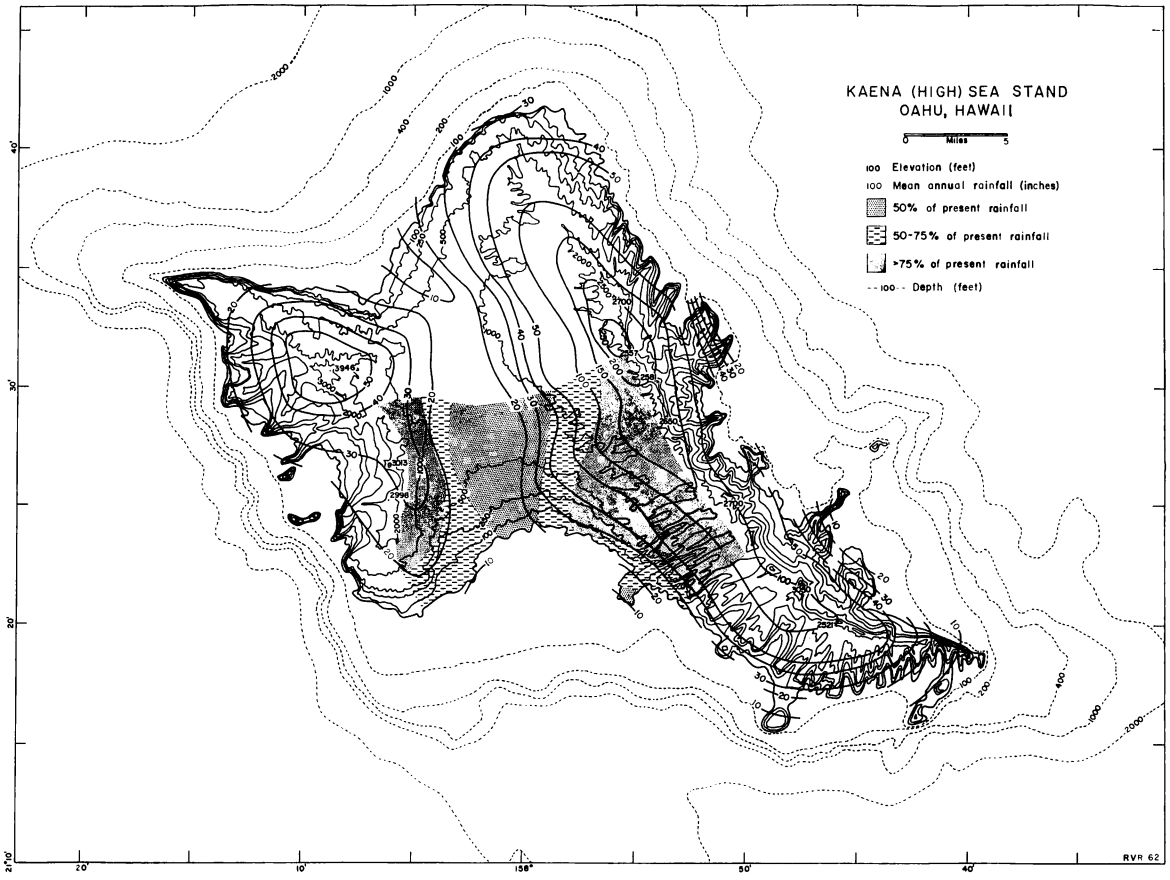

Fig. 4. Relationship of isohyets to topography during Kaena, +100 foot, sea stand, Oahu, Hawaii. Shaded areas compare rainfall of Kaena time to present.

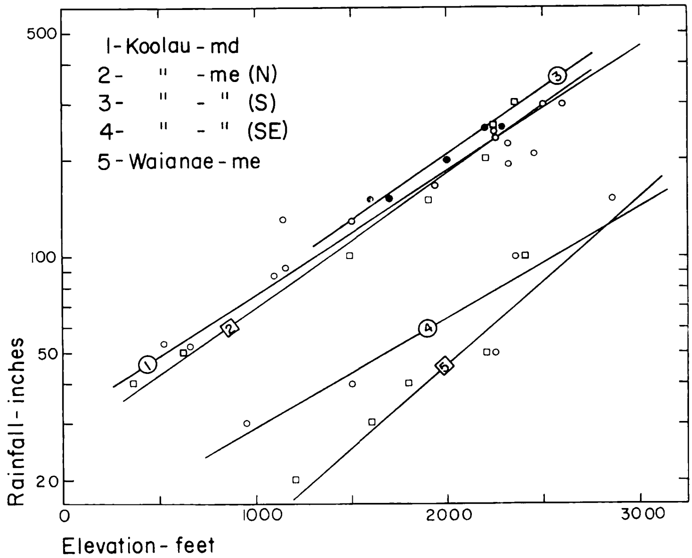

Fig. 5. Relationship of median and mean annual rainfall to elevation along the summit axes of the Koolau and Waianae Ranges, Oahu, Hawaii. See table 1.

surface, varying the topographic surface for two situations, and calculating the isohyetal pattern for each case.

PRESENT REGIMEN

The present isohyetal pattern of Oahu consists of two elliptically elongate ridges with an intervening trough (fig. 1). The eastern ridge is superimposed on the topographic ridge of the Koolau Range, the western ridge on the topographic ridge of the Waianae Range, and the intervening trough on the topographic Wahiawa Basin (fig. 2). High rainfall zones correspond to topographic highs, isohyetal slopes to topographic slopes, and low rainfall zones to topographic lows. Elongate axes of both isohyetal and topographic surfaces are almost at right angles to movement of air masses of the easterly and northeasterly trades. The axis of the Koolau Range trends N 30° W. Median annual wind direction during 1951-60 at Honolulu was N 55° E. Median summer (June-August) wind direction was N 53° E, and median winter (January-March) wind direction was N 63° E. Angles of incidence of trade winds are 85°, 83°, and 93° respectively.

The apparent relationship of rainfall to elevation (Landsberg, 1951) can be tested along the summit axes of the Koolau and Waianae Ranges. The first test relates median annual rainfall to elevation of rain gage stations (Taliaferro, 1959) along the axis of the Koolau Range (fig. 5, 1; fig. 2, 1 to 3). Further test relates median annual rainfall to elevation of rain gage stations (Taliaferaxes of the Koolau and Waianae Ranges (fig. 5, 2 to 5; fig. 2, 1 to 3, 30 to 39; cf. fig. 1). Rainfall is related to elevation as expressed by the equation:

$$\log Y = a + bX,$$

where Y is median or mean annual rainfall in inches and X is elevation of a

TABLE 1

Summary of computation

Rainfall related to	Regression equation	Sy[1]	r[2]	Probability[3]
Elevation of summit				
Koolau summit				
1, 2, 3[4]	$\log Y = 1.4885 + 0.00039X$	27.6	+0.994	99.9
1	$\log Y = 1.4225 + 0.00042X$	20.8	+0.973	99.9
2	$\log Y = 1.4812 + 0.00042X$	7.1	+0.992	99.9
3	$\log Y = 1.0879 + 0.00036X$	17.7	+0.919	95.0
Waianae summit				
30	$\log Y = 0.6001 + 0.00053X$	12.8	+0.886	95.0
31	$Y = -69.162 + 0.042X$	4.2	+0.987	95.0
Distance from summit				
Koolau windward				
4	$\log Y = 1.9849 - 0.0050X$	3.8	-0.989	99.9
5, 11, 12, 13	$\log Y = 2.1450 - 0.0073X$	8.5	-0.978	99.9
6, 9, 10	$\log Y = 2.2990 - 0.0091X$	8.3	-0.987	99.9
7, 8	$Y = 268.072 - 2.321X$	19.5	-0.960	99.9
14, 15	$\log Y = 1.9651 - 0.0080X$	6.8	-0.966	99.9
Koolau leeward				
17, 18, 25, 26, 27, 28	$\log Y = 2.0753 - 0.0051X$	19.5	-0.991	99.9
19, 20, 21, 22	$Y = \frac{1}{0.00297 + 0.00013X}$	35.0	-0.924	99.9
23, 24	$\log Y = 2.2743 - 0.0066X$	14.4	-0.974	99.9
Waianae windward				
32, 38, 39	$\log Y = 1.6087 - 0.0022X$	3.9	-0.902	99.9
33, 34	$\log Y = 1.9294 - 0.0059X$	9.3	-0.904	99.9
35, 36, 37	$\log Y = 1.9528 - 0.0039X$	7.8	-0.905	99.9
Waianae leeward				
30, 40, 41	$\log Y = 1.9265 - 0.0058X$	9.3	-0.942	99.9
42, 43, 44	$\log Y = 1.6178 - 0.0028X$	3.6	-0.926	99.9

[1] Standard estimate of error in inches of rainfall.

[2] Coefficient of correlation.

[3] Level of probability in percent.

[4] This equation weather stations along summit in median annual rainfall in inches; all other equations of isohyets in mean annual rainfall in inches; numbers are traverses shown in figure 2.

gaging station or contact of isohyet and topographic contour.[3] Standard estimates of error are 4 to 28 inches of rainfall. Coefficients of correlation are 0.886 to 0.982 at probability levels of 95.0 to 99.9+ percent (table 1). Therefore, along the summit axes of the mountain ranges median and mean annual rainfall are related to elevation.

The relationship of rainfall to elevation can be tested along traverses on the windward and leeward slopes of the mountain ranges (fig. 2, 4 to 15, 16 to 29, 32 to 38, 40 to 44). Without resorting to statistical testing, scan of plots of the data shows somewhat reasonable relationships in some cases but complex

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[3] Isohyets constructed from 130 gages for 20-year period.

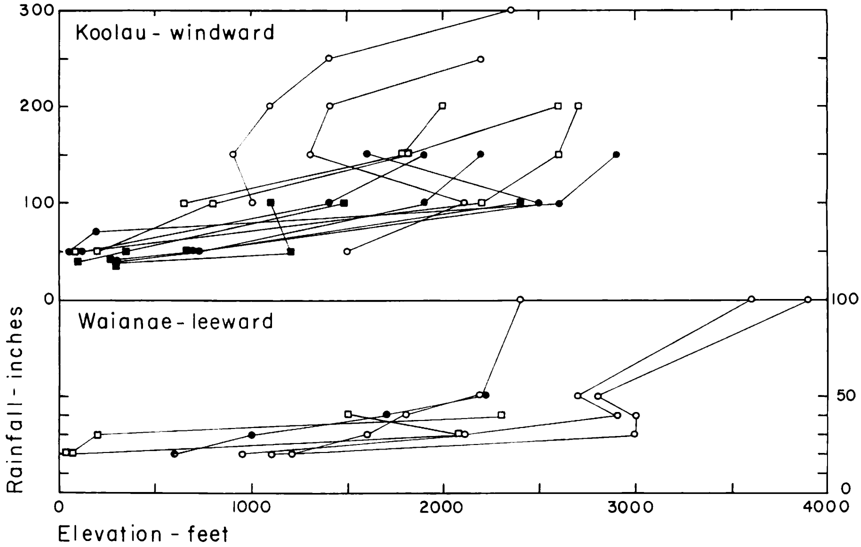

Fig. 6. Relationship of mean annual rainfall to elevation windward and leeward of summit axes of mountain ranges, Oahu, Hawaii.

and somewhat haphazard relationships in others (fig. 6). For example, on the windward side of the Koolau Range high rainfall relates to high elevation with systematic decrease to low rainfall at low elevations in some areas. In other areas there is reversal or inversion of these values. Leeward of the Waianae summit similar conditions are prevalent. An explanation of these phenomena may be in the general expression of local air-mass conditions. However, as all stations were selected along the axes of interfluves descending from the summit axes of the mountain ranges to the coast or interior basin, local variations due to valleys should be negated. Rainfall, then, is not related strictly to elevation on the windward and leeward slopes of the Koolaus and Waianaes.

As the air masses from the east and northeast rise up the windward slopes and undergo adiabatic cooling, condensation is followed by maximum precipitation along the summit. Persistence of the easterly and northeasterly trades should control geographic distribution of the rainfall. As rainfall decreases both windward and leeward from the isohyetal high along the summit, the distribution appears to be related to planimetric distance in both directions from the summit (fig. 1). Voorhees (1929) previously showed that distance of a station from the crest of a mountain is of more importance than elevation in regard to the amount of rainfall at the station. This relationship can be tested along traverses from the summit of a mountain range both to windward and leeward (fig. 2, 4 to 15, 16 to 24). When all data are scaled and grouped, rainfall is related to distance from the summit as expressed by the equation (fig. 7):

$$\log Y = a - bX,$$

where Y is mean annual rainfall in inches and X is the distance in miles of a station windward or leeward of the summit of the range. Data are scaled and grouped by shifting rainfall values of summit points of origin of traverses to

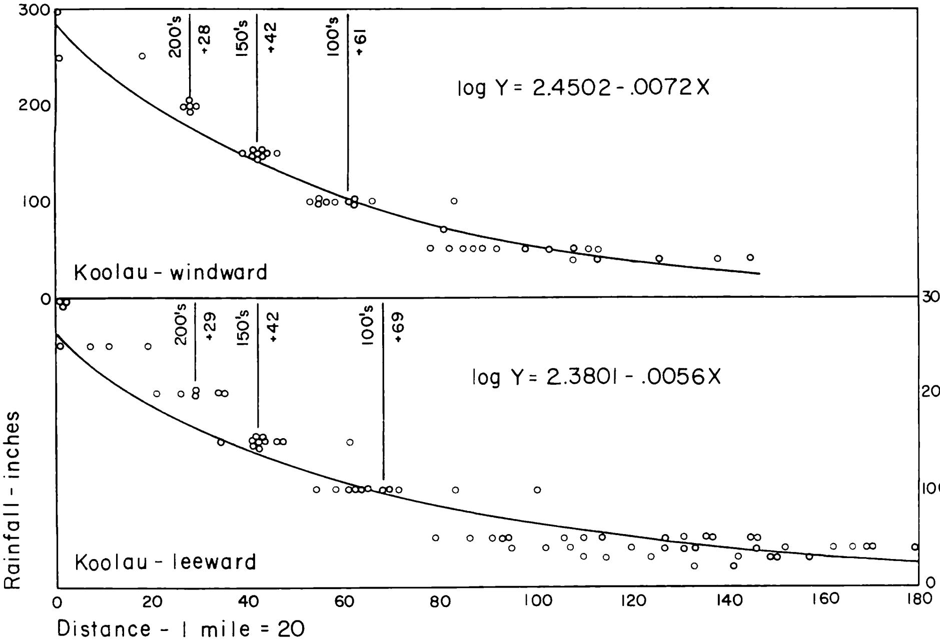

Fig. 7. Relationship of mean annual rainfall to distance to windward and leeward from summit axes of mountain ranges, Oahu, Hawaii. Data scaled and grouped.

equal values of rainfall of other traverses. For example, the origin point of traverses of 200 inches of rainfall and less is shifted to the midpoint of the 200-inch value in the distribution whose origin point is 300 inches of rainfall. Similarly, origin points of traverses of 150 inches and less and 100 inches and less are shifted to the next preceding grouping (fig. 8). In the scaled and grouped data standard estimates of error for rainfall distribution on the Koolau Range to windward and leeward are 14 and 24 inches respectively. Coefficients of correlation are –0.994 and –0.980 at probability levels of > 99.9 percent. Therefore, the rainfall distribution on the windward and leeward slopes of the mountain range is related to distance from the summit.

When rainfall is related to distance along individual traverses, data fall into groups that are a family of curves (fig. 8). The curves are expressed by the equations:

$$Y = a - bX,$$

$$\log Y = a - bX,$$

$$Y = \frac{1}{a + bX}.$$

Standard estimates of error range from 3.6 to 35 inches of rainfall, coefficients of correlation from –0.902 to –0.989 at probability levels of > 99.9 percent (table 1). The network of curves along the summit axes and to windward and leeward of the Koolau and Waianae Ranges expresses the mathematical fit of the present isohyetal pattern to the present topographic surface.

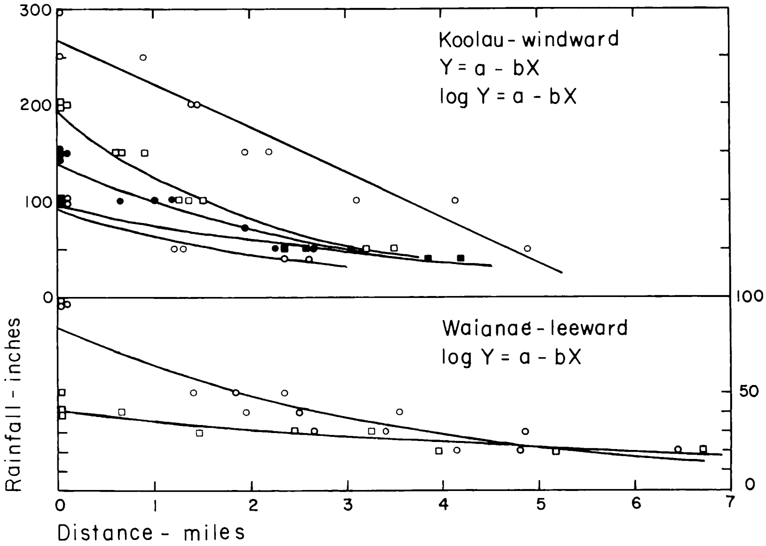

Fig. 8. Relationship of mean annual rainfall to distance to windward and leeward along individual traverses from the summit axes of mountain ranges, Oahu, Hawaii. See table 1.

PAST REGIMENS

Lowering of sealevel 350 feet during the Mamala stand raised all stations on Oahu 350 feet relative to the sea (fig. 3). The curves expressing the relationship of rainfall to elevation along the summit axes of the mountains during that time should have had the same curvature and slope as the curves expressing the present relationship, assuming that the general atmospheric circulation then was similar to the present. The vertical spatial relationships (X axis coordinates) of all stations are uniformly changed. By using the equation log Y = 1.42248 + 0.00042X (table 1) for the higher elevations on a part of the Koolau Range, rainfall values can be calculated. For example, at present a station has an elevation of 2350 feet and rainfall of 300 inches. In Mamala time the station's elevation would have been 2700 feet and its calculated rainfall 360 inches. Rainfall values at all stations along the summit axes of the Koolau and Waianae Ranges are determined by similar calculations. Base lines of the network (fig. 2, 1 to 3, 30 to 39) are established for that time.

Distances from summit axis and between stations along the traverses on the windward and leeward slopes of the mountain ranges were the same in Mamala time as at present. To calculate rainfall on the slopes the family of curves (table 1) are fitted to the rainfall values of the summit base line values calculated for Mamala time. A net for that time is constructed as for the present (fig. 2). Isohyets are constructed from the calculated points and a paleoisohyetal map of Mamala time constructed (fig. 3).

When sealevel was 100 feet higher in Kaena time, elevations of all stations on the island were lowered correspondingly 100 feet relative to sealevel (fig. 4). Values for summit base lines and traverses on windward and leeward slopes are calculated, and the net constructed. A paleo-isohyetal map for Kaena time, in turn, is constructed from the plotted data (fig. 4). Calculated rainfall on the Koolau summit is 267 inches during Kaena time compared to 300 inches at present.

COMPARISON OF PAST AND PRESENT REGIMENS

Calculated rainfall of 360 inches on the Koolau summit during the Mamala low sea stand is not an unreasonable value. On the island of Kauai west of Oahu present median annual rainfall on the summit of Mount Waialeale is 466 inches at an elevation of 5075 feet. Maximum annual rainfall from records of 46 years is 624 inches. Median annual rainfall on the summit of Puu Kukui, West Maui, is more than 400 inches at an elevation of more than 5000 feet (Taliaferro, 1959). On Kaala summit in the Waianae Range, Oahu, rainfall was slightly greater than at present—114 inches versus 100 inches.

Assuming persistent easterly and northeasterly trades during Mamala time as in the present, the greater amount of rainfall over Koolau summit, 20 percent more than present, resulted in a broader distribution pattern on the slopes of the range. Broadening of the elliptically elongate isohyetal ridge was asymmetrical to the west relative to the summit axis of the range. For example, the 100-inch isohyet shifted 2½ times its present distance from the summit axis leeward into the Wahiawa Basin, whereas the windward 100-inch isohyet shifted seaward only 1¼ times its present distance. The isohyetal ridge over the Waianae Range also broadened. Correspondingly, the windward and leeward flanks of the mountain ranges and the interior Wahiawa Basin were wetter than at present.

By comparing the rainfall distribution of the Mamala stand with the present, relative changes can be calculated. In Mamala time a salient from Pearl Harbor extending northward into the Wahiawa Basin had more than 100 percent more rainfall than present (fig. 3). Semiconcentrically around this salient, a zone, low on the bounding mountain slopes and extending northward across the Wahiawa Basin had 50 to 100 percent more rainfall than present. Another zone on the mid-mountain slopes to the east and west had 25 to 50 percent more rainfall than present. High on the mountain slopes and summits to east and west rainfall was 25 percent more than present.

The calculated values for Mamala time would be minimum values if, for example, the theoretical change of climate of Willett (1950, p. 181) is accepted. Stronger, steady easterly trade winds with increased storminess (Brooks, 1949, p. 59) would have caused greater rainfall over Oahu during the glacial maximum. The rainfall distribution would have had the same pattern (Stidd and Leopold, 1951, p. 30), but absolute values would have differed.

During the Kaena high sea stand rainfall on the Koolau summit was about 267 inches or 12 percent less than the present amount. On Kaala summit in the Waianae Range rainfall was about 82 inches or 18 percent less than at present. Again assuming trades similar to today, the elongate isohyetal ridges narrowed. The leeward 100-inch isohyet on the Koolau Range shifted windward three-tenths of the distance of the present 100-inch isohyet from the summit axis. The windward 100-inch isohyet shifted leeward also three-tenths of the distance of the present 100-inch isohyet from the summit axis. Along the

TABLE 2

Relationship of soils and climate on Oahu, Hawaii

Soil	Climate		
	Present[1]	Mamala	Kaena
Low Humic Latosol	10-80 inches annual rainfall; long pronounced dry season; less than 2 inches per month 6 to 10 months per year.	More than 100% more to 25-50% more rainfall than present.	Less than 50% to 50-75% as much rainfall as present.
Humic Latosol	40-150 inches annual rainfall; more uniformly distributed annually; more than 3 inches per month 10 to 12 months of year and more than 5 inches per month 4 to 12 months per year.	Not calculated.	Not calculated.
Hydrol Humic Latosol (soil not present on Oahu)	75-300 inches annual rainfall; more than 5 inches per month throughout year and more than 10 inches per month 3 to 12 months per year.	———	———
Humic Ferruginous Latosol	In wettest parts of climatic zone of Low Humic Latosols and extend into climatic zone of Hydrol Humic Latosols.	More than 25-50% more and 50-100% more rainfall than present.	50-75% and more than 75% as much rainfall as present.

[1] From M. G. Cline, 1955.

north-south axis of the Wahiawa Basin a broad zone had 50 percent less rainfall than present (fig. 4). On the adjacent low mountain slopes to the east and west, two somewhat narrower zones had 25 to 50 percent less rainfall than present. Adjacent zones to the east and west had 25 percent less rainfall than present.

The calculated values for Kaena time would be maximum values if the theoretical climatic change of Willett (1953, p. 55) is accepted. Interglacial displacement of zonal westerlies and cyclonic storminess of middle latitudes into the higher latitudes should have produced generally settled, mild, storm-free conditions with deficiency of rainfall in the more southerly storm tracks. Oahu should have been drier than calculated.

The possibility of these climatic changes, wetter in Mamala time and drier in Kaena time, has direct implication in genetic interpretation of soils in the Wahiawa Basin. A systematic zonality of present climate in relation to the mountainous masses of the islands and an associated zonality of soils was previously recognized (Cline, 1955). Correlation was drawn between the soils and present zones, and inferences made of the effect of present climatic factors in the genesis of the soils. The zones of soils and present climate are given in table 2, and the complications introduced by climatic changes are also given. An immediate conclusion is that the soils are a result of a summation of the effects of all of the climates, among other factors, and not just of the present. It is extremely difficult to assign responsibility of any one episode of climate as having greater influence in affecting the formation of a soil than any other episode.

REFERENCES

Arrhenius, G. O. S., 1952, Sediment cores from the east Pacific: Swedish Deep-Sea Exped. 1947-48, Repts., v. 5, fascicle 1, 227 p.

——— 1959, Climatic records on the ocean floor, p. 121-129, *in* The atmosphere and the sea in motion, Scientific contributions to the Rossby memorial volume: New York, Rockefeller Inst., 509 p.

Brooks, C. E. P., 1949, Climate through the ages, 2d. ed.: New York, McGraw-Hill Book Co., 395 p.

Blumenstock, D. I., 1961, Climate of Hawaii: U. S. Weather Bur., Climatography of U. S., no. 60-51, 20 p.

Cline, M. G., 1955, Soils and climate, *in* Soil Survey, Territory of Hawaii: U. S. Dept. Agr. Soil Survey ser. 1939, no. 25, p. 85-95.

Donn, W. L., Farrand, W. R., and Ewing, M., 1962, Pleistocene ice volumes and sea-level lowering: Jour. Geology, v. 70, p. 206-214.

Emiliani, Cesare, 1955, Pleistocene temperatures: Jour. Geology, v. 63, p. 538-578.

——— 1961, Cenozoic climatic changes as indicated by the stratigraphy and chronology of deep-sea cores of Globigerina-ooze facies: New York Acad. Sci. Ann., v. 95, p. 521-536.

Feldwisch, W. F., 1941, Climate of the Hawaiian Islands, *in* Climate and Man, Yearbook of Agriculture: U. S. Dept. Agr., p. 1216-1221.

Lamb, H. H., 1961, Fundamentals of climate, *in* Descriptive paleoclimatology: New York, Intersci. Publishers, Inc., p. 8-43.

Landsberg, H., 1951, Statistical investigations into the climatology of rainfall on Oahu (T.H.): Meteorol. Mon., v. 1, no. 3, p. 7-23.

Leopold, L. B., 1949, The interaction of trade-wind and sea breeze, Hawaii: Jour. Meteorology, v. 6, p. 312-320.

——— 1951, Hawaiian climate—its relation to human and plant geography: Meteorol. Mon., v. 1, no. 3, p. 1-6.

Riehl, H., 1954, Tropical meteorology: New York, McGraw-Hill Book Co., Inc., 392 p.

——— 1962, General atmospheric circulation of the tropics: Science, v. 135, p. 13-22.

Russell, R. J., 1963, Recent recession of tropical cliffy coasts: Science, v. 139, p. 9-15.

Schell, I. I., 1949, Comments on H. C. Willett's "Long-period fluctuations of the general circulation of the atmosphere": Jour. Meteorology, v. 6, p. 225.

———— 1961, Recent evidence about the nature of climate changes and its implications: New York Acad. Sci. Ann., v. 95, art. 1, p. 251-270.

Shepard, F. P., 1961, Sea level rise during the past 20,000 years: Zeitschr. Geomorphologie, supp., v. 3, p. 30-35.

Simpson, G. C., 1934, World climate during the Quaternary Period: Royal Meteorol. Soc. Quart. Jour., v. 60, p. 425-478.

Solot, S. P., 1950, Further studies on Hawaiian precipitation: U. S. Weather Bur. Research Paper 32, 37 p.

Stearns, H. T., 1935a, Shore benches on the island of Oahu, Hawaii: Geol. Soc. America Bull., v. 46, p. 1467-1482.

———— 1935b, Pleistocene shorelines on the islands of Oahu and Maui, Hawaii: Geol Soc. America Bull., v. 46, p. 1927-1956.

———— 1961, Eustatic shorelines on Pacific Islands: Zeitschr. Geomorphologie, supp. v. 3, p. 3-16.

Stearns, H. T., and Vaksik, K. N., 1935, Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii [Terr.] Dept. Public Lands Div. Hydrology Bull. 1, 479 p.

Stidd, C. K., and Leopold, L. B., 1951, The geographic distribution of average monthly rainfall, Hawaii: Meteorol. Mon., v. 1, no. 3, p. 24-33.

Taliaferro, W. J., 1959, Rainfall of the Hawaiian Islands: Hawaii Water Authority, Honolulu, 394 p.

U. S. Weather Bureau, 1962, Decennial census of United States climate, Honolulu, Hawaii: Climatography of U. S., no. 82-51, 16 p.

Voorhees, J. F., 1929, A quantitative study of rainfall of the island of Oahu: Honolulu Sewer and Water Comm. Rept., supp., p. 294.

Wentworth, C. K. and Palmer, H. S., 1925, Eustatic bench of islands of North Pacific: Geol. Soc. America Bull., v. 36, p. 521-544.

Willett, H. C., 1949a, Long-period fluctuations of the general circulation of the atmosphere: Jour. Meteorology, v. 6, p. 34-50.

———— 1949b, Solar variability as a factor in the fluctuations of climate during geological time: Geog. Annaler, v. 31, p. 295-315.

———— 1950, The general circulation at the last (Würm) glacial maximum: Geog. Annaler, v. 32, p. 179-187.

———— 1953, Atmospheric and oceanic circulation as factors in glacial-interglacial changes of climate, *in* Shapley, H., ed., Climatic Change: Cambridge, Harvard Univ. Press, p. 51-71.

Yeh, T. C., Wallen, C. C., and Carson, J. E., 1951, A study of rainfall over Oahu: Meteorol. Mon., v. 1, no. 3, p. 34-46.

Yeh, T. C. Carson, J. E., and Marciano, J. J., 1951, On the relation between the circumpolar westerly current and rainfall over the Hawaiian Islands: Meteorol. Mon., v. 1, no. 3, p. 47-55.