Anomalous Orographic Rains of Hawaii[1,2]

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(Manuscript received 22 October 1974; in revised form 23 December 1974)

ABSTRACT

Observations, on the island of Oahu, Hawaii, of unusual rains and clouds in marine air during fresh easterly winds show that rain can form within and fall continuously from a shallow layer of warm stratocumulus in about 5 to 13 minutes. This time estimate is shown to be dependent upon where, in the rapidly moving marine cloud system, an island effect initiating raindrop growth is assumed to begin. The clouds are associated with frontal passage nearby, and they form light rains of about 1 to 8 mm/h, averaging 3.5. On the windward shore the clouds produce sparsely distributed showers, suggesting a cell-like structure of the rain development processes over the sea, whereas a few kilometers inland over the Koolau Mountain Range they produce continuous rain and then quickly dissipate. The raindrop-generating processes seem to occur largely over the island rather than over the windward sea, as has been previously suggested concerning the more common orographic showers from the northeasterly tradewind cumuli. The unusually short raindrop-formation times revealed are thought to require some modification of current ideas about the collision-coalescence process of raindrop growth in these oceanic clouds. It is suggested that turbulence in the clouds caused by passage over Oahu may accelerate the collision-coalescence process and thus reduce the raindrop growth times.

1. Introduction

The rains of Oahu have long been a subject of study. An extensive network of recording and non-recording raingages on the island contribute largely to these studies, and reflect the intense local interest in water for agricultural and human consumption. Island rainfall as a function of weather pattern, season, elevation, wind direction, distance from the crest of the mountains, and other parameters, has been investigated [Leopold, 1949, 1951; *Meteorological Monographs*, 1951; Mink, 1962; and others (see annotated bibliography on Hawaiian weather by Ekern and Worthley, 1968)].

The Koolau Mountain Range (KMR) of Oahu, which is about 45 km long, 600 m high, and only a few kilometers from the windward shore (Fig. 1), rises as a great barrier across the prevailing northeast winds (also called the trade winds or simply the trades), forces the winds upward, and forms the well-known orographic clouds and rains of the island.

Much of the annual rainfall over the KMR is orographically produced within oceanic cumulus clouds which are transported over the range by the northeasterly winds (Yeh *et al.*, 1951). The high rainfall areas on the mountain ridges and valleys are just over the crest of this range (Taliaferro, 1959). Mordy and Eber (1954) suggested that the increased rainfall in the valleys is due to an orographically enhanced growth of raindrops falling from clouds that were already producing rain over the windward sea before they arrived over the island.

The occurrence of rain over the KMR during trade winds was thus assumed to depend upon the preexistence of rain in the clouds before they reach the island. Blanchard (1953a) concluded that, under ordinary tradewind conditions, time was insufficient for raindrop formation by the collision-coalescence process during the approximately 20 min required for passage of the clouds from the shore to the mountains. This conclusion was supported later by a radar study of the accretional growth of showers in warm cumuli of North Atlantic NE tradewind areas (Saunders, 1965). Saunders showed that from 25 to 35 min were required for raindrops to grow to a diameter of ~ 0.5 mm. During that interval the clouds, which were over the ocean, grew from a "fractocumulus stage to a cumulus congestus"; an additional 6 to 10 min was required for a shower to grow and to fall from the clouds. Similar results were reported by Moore (1974) from radar observations among other tradewind cumuli which passed over an island in the same area.

According to Saunders' study, clouds forming largely over Oahu after the northeasterly wind passes over the windward shoreline (average speed ~ 8 m s^{-1}) would probably be carried about 15 km, or well beyond the observed high-rainfall areas of the KMR before rain could form within and fall from them. On Oahu these

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[1] Hawaii Institute of Geophysics Contribution No. 647.

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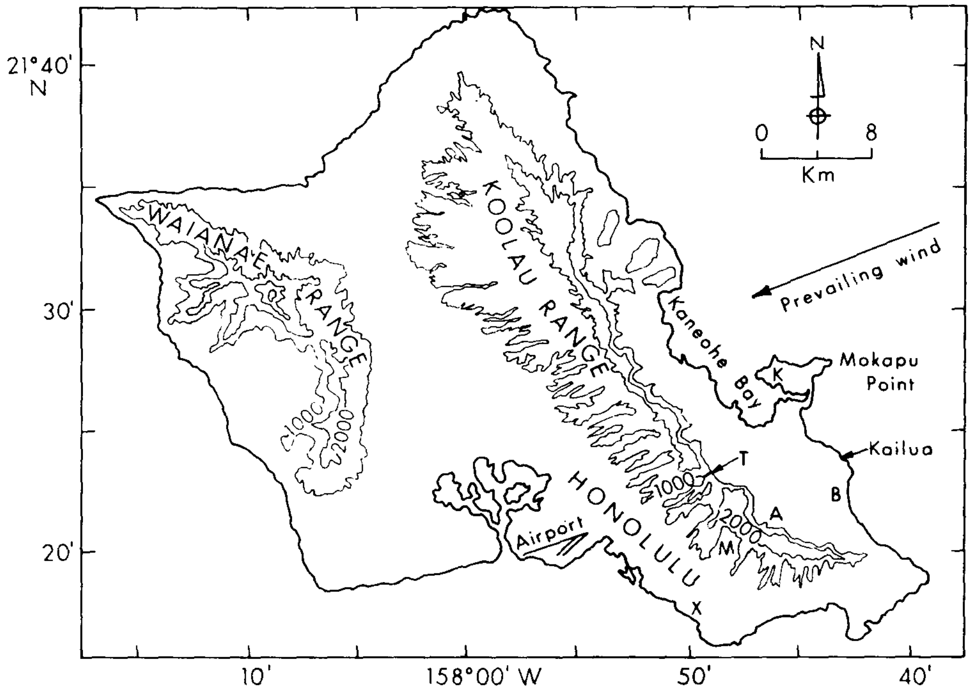

Fig. 1. Contour and location chart of the island of Oahu, Hawaii. Altitudes in feet. See text concerning location areas A, B, K, M, X, and T.

areas are only about 6 to 10 km from the northeasterly shore (Taliaferro, 1959). Thus, in consideration of Saunders' observations it seems that Blanchard, and Mordy and Eber, were right in assuming that shower rain exists in the cumuli over the sea, if about 30 min or more are really required for the production and fallout of raindrops in these clouds.

However, a weakness in the above argument lies in the problem of explaining the low frequency of occurrence of showers along the windward shore as compared with that over the KMR (Blanchard, 1953a). If frequency over the KMR depends upon the preexistence of showers in the air stream over the windward sea, then the number of showers falling on the windward shore should equal the number falling over KMR. However, the number of showers observed along the windward shore was only about one-third the number observed after passage of the clouds over the KMR (*ibid.*).

Recent observations of continuous orographic rain over the KMR during easterly winds further emphasize the weakness of the earlier argument about rainfall. These observations are given below in some detail, since they can be used to support the idea that these continuous rains form in unusually short periods of time. These times appear to be shorter than those estimated from radar observations by Saunders and Moore, or those theoretically derived by Twomey (1966) and Nelson (1971).

2. Anomalous rains

The usual orographic rains of Hawaii during tradewind conditions are showery, with the dimensions of the rain shafts about 2 to 3 km in diameter (Squires and Warner, 1957). Several times a year, however, the orographic rains associated with cold front passage and northeasterly winds are unusual, for they are relatively steady and extend over the full length of the KMR. In contrast to the common intermittent tradewind showers, I have called these rare steady rains anomalous orographic rains (AOR); see Fig. 2. Figure 3 illustrates the marked difference in the nature of these rains.

In the light of the foregoing remarks about earlier studies of orographic rains in Hawaii, it would seem that, during the AOR condition, there should be an associated continuous but probably less intense rainfall from the clouds over the windward sea and shore as well. Figure 4 shows, however, that this is not the case.

Figure 5 shows that on all of the AOR days (Table 1) rainfall was low along the windward shore while high along the KMR. We seem required, therefore, to assume one of two explanations: a) that on AOR occasions all of the stratocumulus clouds over the sea have simultaneously reached the rain-formation stage with the clouds before the clouds arrive over Oahu; or b), that these rains form largely after the cloud stream encounters the island and/or the mountain barrier. The first explanation seems highly unlikely, implying as it does the nearly identical life histories and durations of

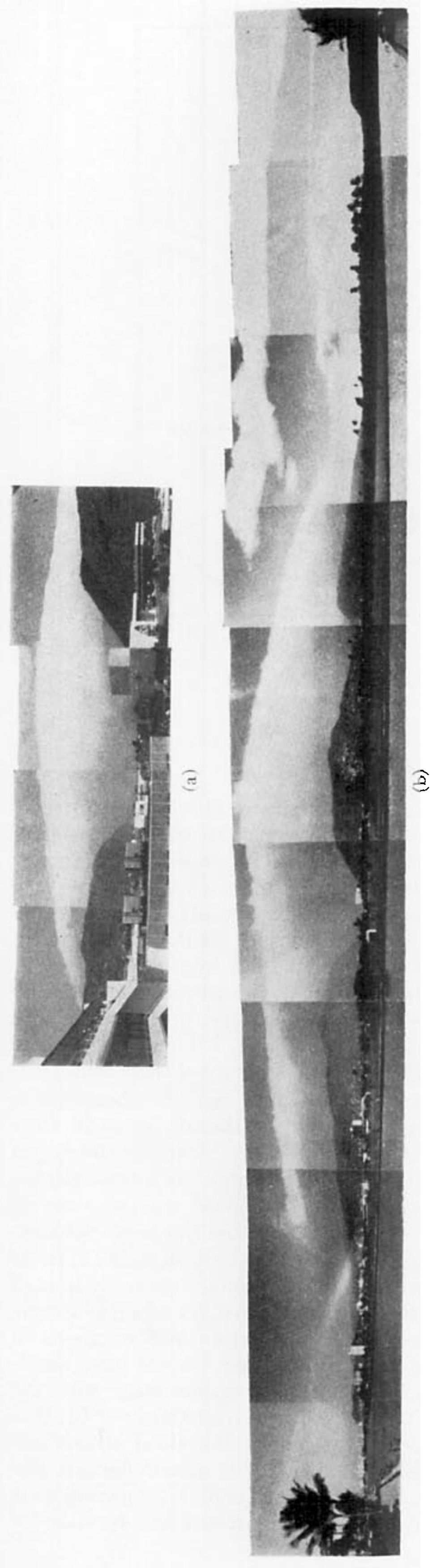

FIG. 2. Photographs of AOR clouds over the KMR when northeast winds were ~7 $m \cdot s^{-1}$ at cloud levels; (a) showing a view up Manoa Valley (at M, Fig. 1), looking northeast from the University of Hawaii at about 1400 LMT 23 March 1965, cumulus tops ~1800 m; and (b), a view in the same direction from the Ala Wai Canal (at X, Fig. 1), 1000 LMT 4 December 1968, cumulus tops ~2100 m, when AOR was observed over a major portion of the mountain range. The valley to the left is Manoa, and that to the right is Palolo, where the rainfall rates at the time were 3.6 mm h^{-1}, while gages 882.12 and 882.4 (Fig. 5) at the northwest end of the KMR showed a rate of 3.4 mm h^{-1}. This 1968 AOR lasted ~12 h, while on the windward shore the maximum rainfall recorded was three brief showers totaling 15 min.

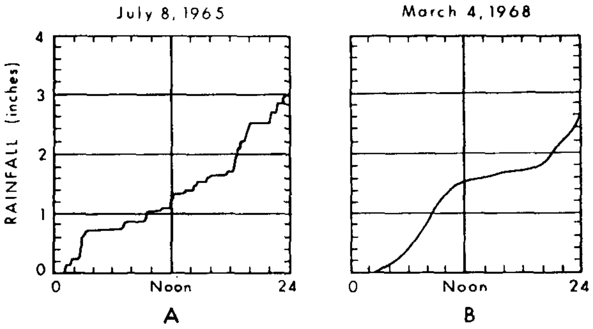

FIG. 3. Diagram showing the contrasting nature of the rain records from raingage no. 716 during (A) trade-wind orographic showers, and (B) during the continuous rains of an AOR period.

the clouds over the sea prior to arrival over the island or that the orographic effect of Oahu extends 5 to 10 km over the windward sea. The second explanation appears the more likely one, although it requires unusually rapid rainfall growth and fallout.

My purpose here is to show that the stratocumulus (Sc) clouds and AOR conditions may constitute a natural demonstration that the island mass rapidly triggers rain development in the clouds apparently containing little or no rain while they are approaching the island from over the windward sea. This rapid rain formation is discussed below, after a brief description of the conditions associated with the AOR.

a. Rainfall amounts

The rain amounts shown in Table 1 are the mean daily midnight-to-midnight values taken from the records of the 15 universal-type recording gages whose locations are shown on Fig. 5. On each of the 23 days given, the general AOR conditions shown in Fig. 2 were visually observed on the KMR. Figure 4 illustrates the difference in the rain records on the two sides of the KMR; note that sparcely distributed showers fall from the Sc overcast on the windward shore of the island while continuous rains fall on the leeward side of the ridge. This difference will be discussed later.

b. Clouds

On each of the AOR days a Sc cloud deck was visually observed in the air stream over the windward side of the island and over the sea northeast of Oahu. From the available satellite cloud photographs on 16 of the AOR days, we learn that the cloud deck extended from about 100 to 800 km northeastward of Oahu (e.g., see Fig. 6). This means that the clouds forming the continuous rain existed for a long time before arriving over Oahu.

The Sc cloud bases on the AOR days were at about 460 to 610 m, and the tops were from about 1500 m to 2750 m, with an average altitude of 1890 m. These altitudes were derived from observations of Sc bases

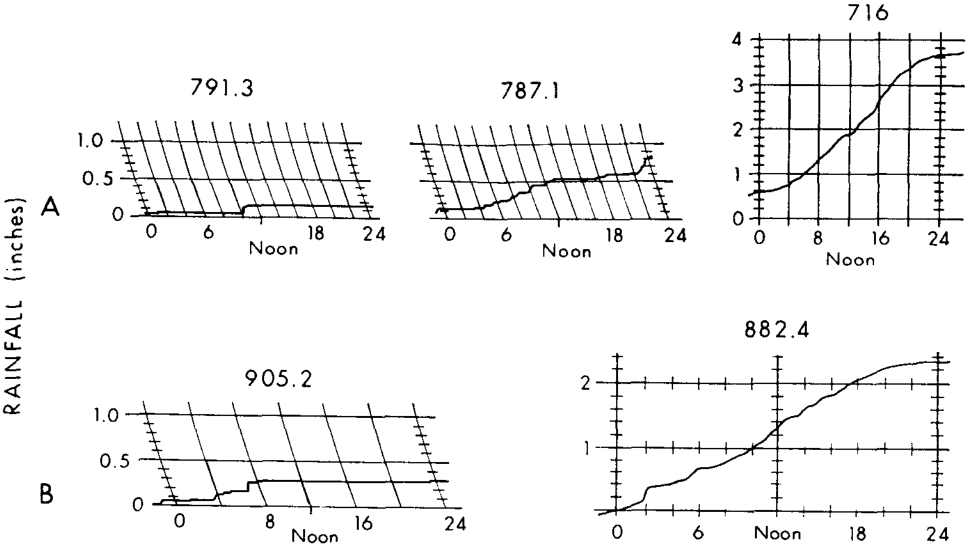

FIG. 4. Traces of AOR records for 24 March 1969, illustrating the transition (left to right) from the sparsely distributed showers falling on the windward shore (stations 791.3 and 905.2) to the continuous rain in the valleys leeward of the KMR (stations 716 and 882.4). Records A represent conditions along a line normal to the ridge near the southeast end of the range, and B the rains simultaneously recorded along a similar line near the northwest end of the range (see Fig. 5 and text).

against the KMR and from pilot reports ("pireps," about eight made daily to the National Weather Service, Honolulu International Airport) during numerous inter-island flights. At Hilo and Lihue, the freezing altitude on the AOR days remained above the 3.2 km level, with the average height at 4.3 km. Un-

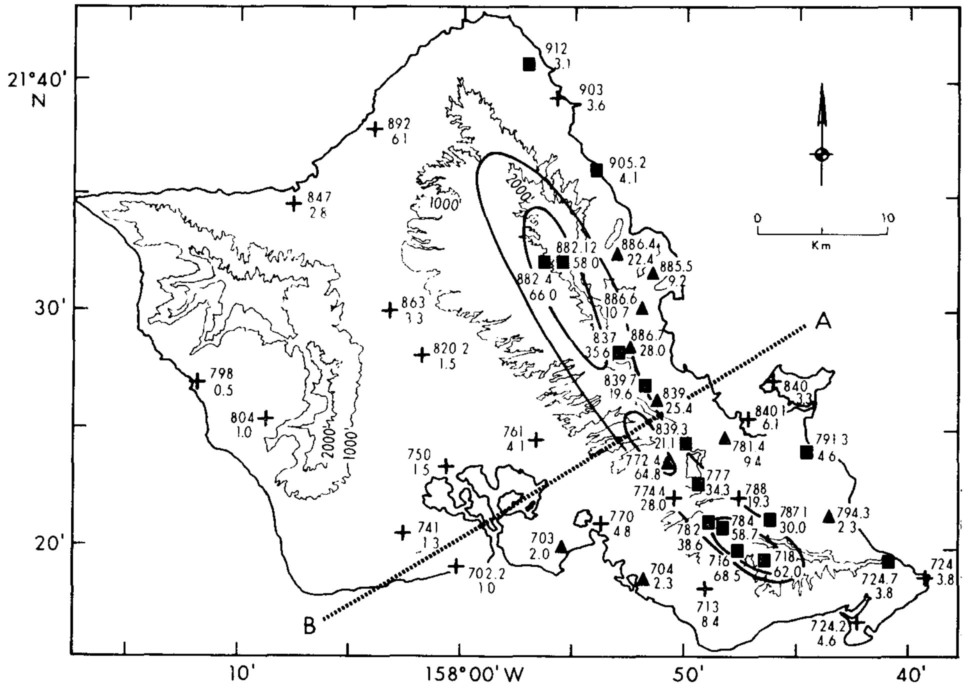

FIG. 5. Contour chart of Oahu showing the location of raingages used in this study. The upper digits indicate the station State Key number, and the lower digits the average daily rainfall amount (mm) during the AOR days. The squares represent universal weighting or water-level recorders; the triangles, the tipping bucket recorders; and the plus signs, the non-recording gages. Isohyetal lines for AOR amounts of 25 and 50 mm are estimated. These lines follow the well-established annual pattern over much of the KMR (see Taliaferro, 1959).

TABLE 1. Mean daily rain amounts and rain durations during 23 AOR days at all standard recording raingage stations on the KMR and on the windward shore of Oahu. Station numbers are given below and their locations are shown in Fig. 5. The winds are means from the Honolulu Airport "pibals," at altitudes from ~400 to 2000 m. Rain "hours" (h) at stations B and C are the summations of the durations of intermittent showers, while at station A they represent extended periods of continuous rain. See text and Fig. 4.

Date	Winds		Rain amount and duration†					
	Speed	Direction	A		B		C	
	m s^{-1}	true	mm	h	mm	h	mm	h
23 Mar. 1965	7.7	ENE	24.2	8.6	7.0	1.0	—	—
1 Dec. 1965	12.0	NNE	40.6	9.3	39.5	4.1	13.5	1.2
6 Dec. 1965	11.4	NE	36.2	9.7	17.0	3.1	8.0	1.5
10 Dec. 1965	7.7	ENE	120.0	18.4	60.0	5.0	2.0	1.8
*13 Aug. 1966	9.4	ENE	22.2	12.7	8.7	1.7	2.5	0.5
*31 Oct. 1966	9.1	NE	97.0	18.7	51.0	5.9	2.0	3.5
*27 Feb. 1967	6.9	NE	93.4	19.1	42.7	7.0	1.3	0.1
1 Mar. 1967	8.4	E	8.4	4.6	3.0	0.6	0.0	0.0
*17 Aug. 1967	8.3	ENE	73.0	18.3	18.7	8.2	10.0	1.8
4 Mar. 1968	6.4	ENE	40.6	18.8	14.3	6.7	1.3	0.4
1 May 1968	no data		21.0	10.1	13.3	2.0	1.5	0.4
4 Dec. 1968	6.7	NNE	52.4	12.9	14.7	5.5	1.0	0.3
12 Dec. 1968	9.7	NNE	32.7	11.3	17.5	4.2	3.0	0.3
*13 Dec. 1968	6.6	NE	39.8	12.4	17.2	3.5	0.3	0.1
31 Jan. 1969	6.8	ENE	46.8	12.8	6.8	1.6	1.2	0.2
14 Feb. 1969	6.1	NE	80.7	21.4	68.7	6.8	2.5	0.7
*15 Feb. 1969	6.3	NE	76.9	20.0	77.0	12.0	8.0	1.7
18 Feb. 1969	9.9	E	65.4	16.1	12.3	3.4	0.8	0.2
19 Feb. 1969	6.9	ENE	57.8	15.6	8.0	1.3	0.2	0.2
*24 Mar. 1969	8.1	NE	60.1	20.7	27.0	7.3	5.2	1.0
25 Mar. 1969	4.8	NE	42.0	10.9	34.2	8.8	7.2	1.2
*29 Apr. 1969	7.1	NE	53.4	18.9	25.2	4.2	1.2	0.3
*10 Sep. 1969	4.6	ENE	33.6	13.4	17.5	4.4	7.2	1.0
MEANS	7.8	NE	55.3	15.5	26.0	5.3	4.0	0.8

† A) KMR stations 716, 718, 777, 782, 784, 882.4, and 883.12.
B) Windward Koolau Mountain-valley stations 787.1, 839.3, 839.7, and 837.
C) Windward coastal stations 724.7, 791.3, 905.2, and 912.

fortunately, the "pireps" for ~60% of the AOR days were lost. Thus, I cannot be sure that the warm-cloud precipitation process predominated during all of the AOR days. However, I saw no exceptions to the low-profile shallow-layer character of the AOR clouds revealed in Fig. 2; hence I am reasonably certain that in all cases we are dealing with warm rain. The cloud-top altitudes given on Fig. 2 were photogrammetrically derived, and correspond closely to the temperature inversion altitude (~2100 m) measured on the date at Lihue, Kauai, the nearest rawinsonde station, which is 170 km west northwest of Oahu. The steadiness and low intensities of the AOR, and the rapid dissipation of the rained-out cloud, are consistent with the shallow-layer origin revealed in the photographs, and supported by the "pireps" on the one-third of the AOR days for which they were available.

The presence of the Sc cloud and AOR was almost always associated with a frontal passage near the islands (e.g., see Fig. 7). Apparently there is a cell-like structure of the Sc cloud under these conditions, for we note the showery nature of the windward rains during the AOR conditions (see Fig. 4). These cells are probably of the closed type indicated by Hubert (1966) and by Agee *et al.* (1973), for the cloud deck was an almost continuous one, as viewed from the windward shore. I have measured cell diameters of 2 to 10 km on other occasions during flights over Sc cloud northeast of the Hawaiian Islands.

c. *Thermal stability*

It seems likely that the sub-cloud layer was thermally unstable during the AOR conditions, since the flow of the surface air tended to have a northerly component and to cross the sea-surface isotherms, which trend approximately east-west in this area of the North Pacific (Wyrtki, 1966). It is unfortunate that there are no rawinsonde data indicating the general thermal structure of the lower atmosphere over Oahu. However, on 20 of the 23 AOR days the rawinsonde measurements at Lihue showed that a temperature inversion was present in the lower air at a mean altitude of 2.3 km, with relative humidities of less than 50% above this altitude.

d. *Winds*

On AOR days the winds over Honolulu were northeasterly, tending to veer towards the east southeast and to diminish in speed above about 1500 m (see Table 1 and Fig. 8). For comparison, average winds are also shown for a similar number of tradewind orographic shower (TOS) days. All of these winds were taken from the six-hourly pilot balloon observations of the National Weather Service (NOAA), at the Honolulu International Airport, and we assume that they represent the winds transporting the Sc clouds over the KMR about 11 km northeast of the airport station (see Fig. 1). The wind speed maximum over Honolulu at the KMR altitude (~600 m) is marked on the AOR days (see Fig. 8), with both AOR and TOS days showing veering and diminishing speed with altitude in the lower levels.

Northeasterly surface winds recorded on the windward shore of Oahu, at Kaneohe Marine Corps Air Station and Bellows Air Force Station (see locations K and B, Fig. 1), averaged 6.3 m·s^{-1} on the AOR days, which is about the same as the Honolulu Airport surface winds. Ship reports of surface winds at sea in the Hawaii region on the AOR days indicated average velocities of 9.8 m·s^{-1} from the northeast. Thus, the mean surface winds at sea were about equal to the mean winds at the KMR altitudes over Honolulu and exceeded surface winds on Oahu by more than 3 m·s^{-1}.

e. *Rain formation time in the Sc clouds*

Using the distances available in Fig. 5, the average speed and direction of motion of the air transporting the Sc clouds over Oahu given in Table 1, and cloud-top observations where available, I have estimated the time required for raindrops to form in and to fall from those clouds. In so doing it is assumed that the rain-forming

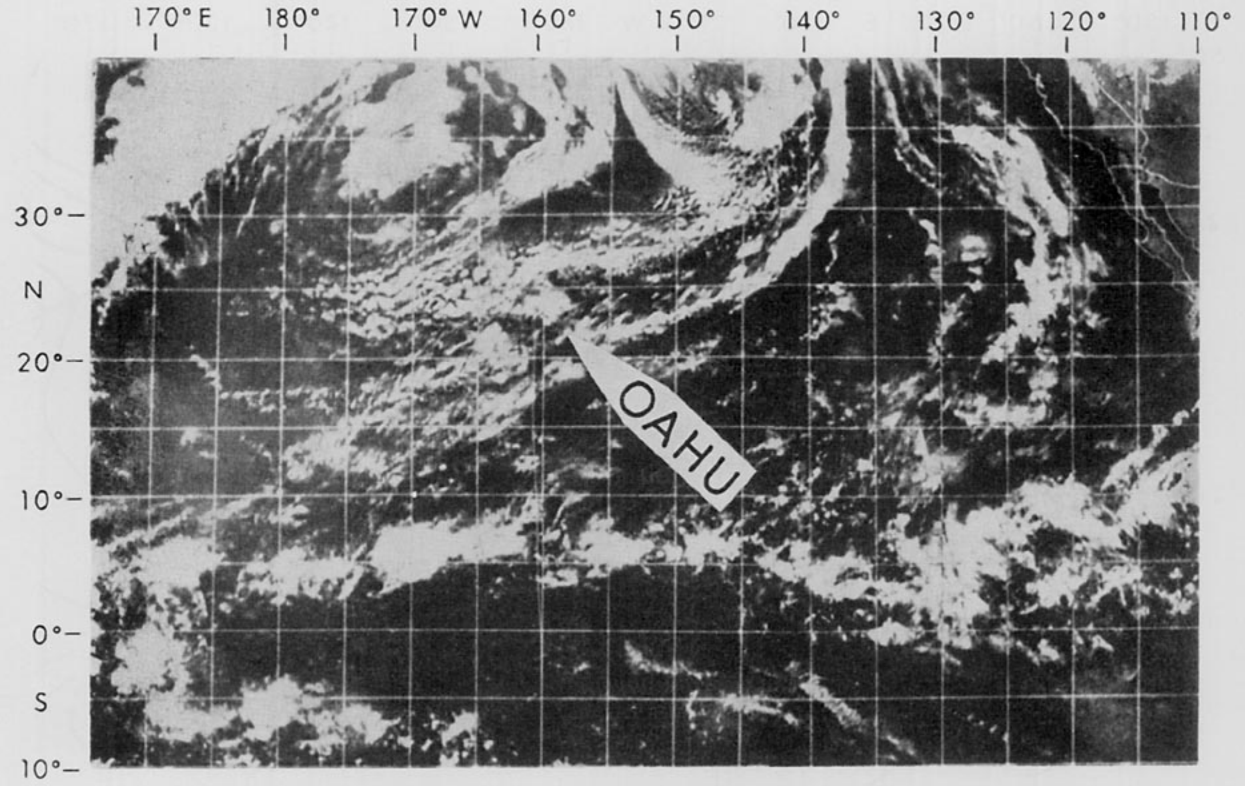

Fig. 6. Satellite photograph of clouds in Hawaiian Islands region (see Oahu marker) during one of the AOR days. ESSA 7 pass 2754–2766, 24 March 1969. See Fig. 7 for associated North Pacific weather chart.

process begins in the clouds as they pass over the shoreline northeast of KMR. On many AOR days little or no rain falls at the windward coastal gage sites, while an average of about 20 times more rain falls at the mountain sites a short distance downwind from the crest of the KMR. As previously noted, distances from the mountain gage sites to the northeast shoreline range from 6 to 12 km. At a mean wind speed of $\sim 8\ \mathrm{m \cdot s^{-1}}$ on AOR days the time required for the clouds to travel the minimum distance (i.e., the apparent rain-drop generation and fallout period) is ~ 13 min. On a day with strongest mean winds ($12\ \mathrm{m \cdot s^{-1}}$ on 1 December 1965, Table 1) the time decreases to ~ 9 min.

One can argue that the veering of the wind with altitude (see Fig. 8) may increase these travel times for those parts of the clouds above about 1600 m by as much as 30%, and thus lengthen the raindrop growth period for them accordingly. However, it is not certain that this added travel time is a decisive factor in accounting for the rapid formation of rain over the KMR. On 9 of the AOR days there was relatively little veering of the winds (see days marked with an asterisk, Table 1), yet there is no indication that on these days the relative excess of the rainfall at the mountain raingage stations decreased as compared with that at the windward shore stations.

Wind shear due to speed differences with altitude will also affect estimates of travel time for those parts of the clouds which are moving more slowly. Note on Fig. 8 that the wind speeds at 2 km on the AOR days average about 50% of the winds at 1 km; since most of the cloud material is apparently well below the 2 km level on the AOR days (e.g., see Fig. 2), however, it seems reasonable to use the mean value of wind speed (i.e., $\sim 8\ \mathrm{m \cdot s^{-1}}$) for estimates of mean Sc cloud transport rate.

f. Windward showers

Our reasoning on the probable local orographic origin of the rapid onset of continuous rain within the Sc clouds over the leeward side of the KMR seems equally applicable to the rapid increase in shower number with distance inland on the windward shore of Oahu (e.g., see Fig. 4A). In other words it reflects an orographic effect and not an increase in the production of showers within the clouds over the sea just prior to their arrival over Oahu.

Thus, the most rapid apparent production of showers in the Sc clouds with distance from the windward shore is shown at stations 837, 839.7, 839.3, and 787.1, which are in mountain valleys immediately below and to windward of the precipitous base of the KMR (see Fig. 5). Unfortunately, there are no rainfall records for the windward Kaneohe Bay shoreline in the area where three of our four windward mountain-base stations lie

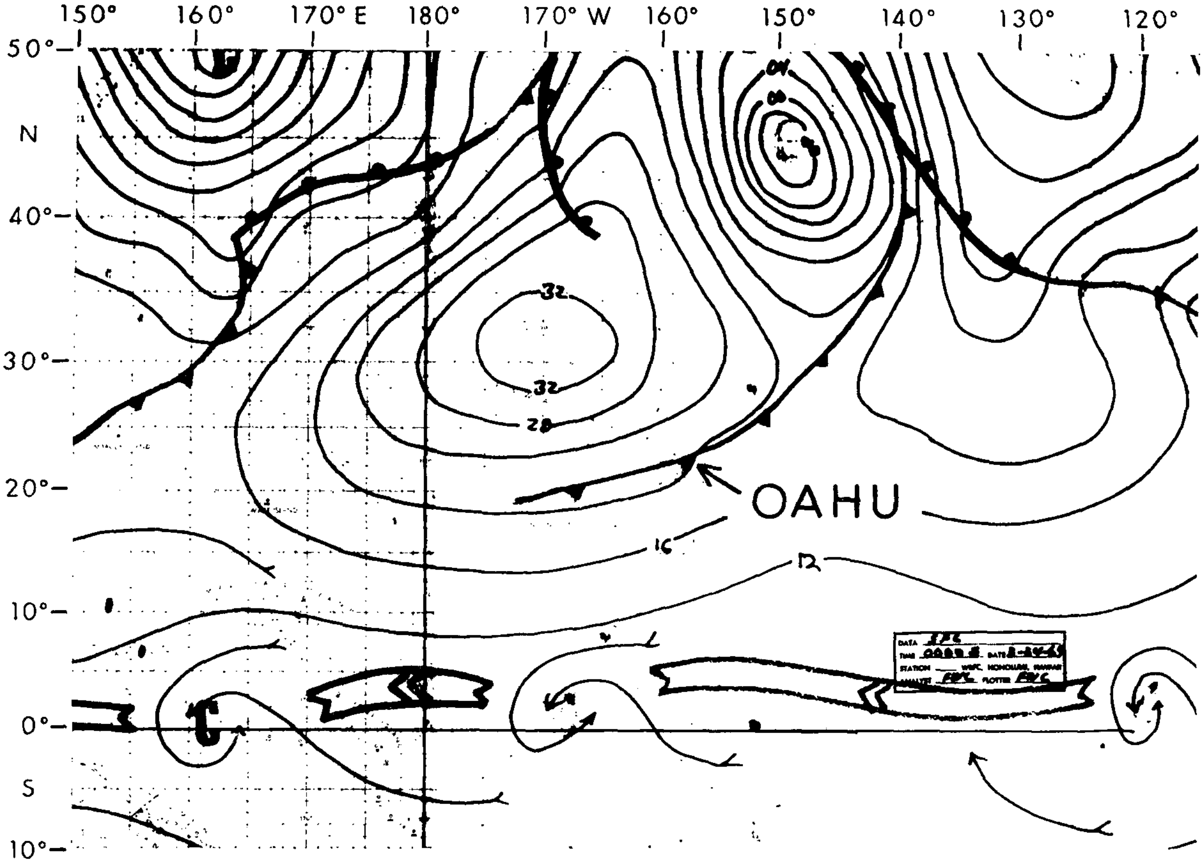

FIG. 7. North Pacific surface weather chart for 0000 GMT 24 March 1969, showing an example of frontal passage associated with an AOR day. Arrow marks Oahu location. Figure 6 shows satellite picture of cloud pattern at this time.

(see Fig. 5). However, if we make the reasonable interpolation from the mean shower number registered at the four coastal stations (724.7, 791.3, 905.2, and 912), we find a mean increase in rainfall from about 2.8 to 9 showers per day within a distance of about 3.5 to 6.5 km. From these distances and the observed mean wind speed on AOR days (i.e., $\sim 8\ \mathrm{m \cdot s^{-1}}$) we estimate that average production times of these additional showers are about 7 to 14 min.

3. Discussion and additional observations

The average rainfall during the AOR conditions among the 9 stations to leeward of the crest of the KMR (i.e., $53.2\ \mathrm{mm \cdot d^{-1}}$) is about 15 times that among the 8 stations near the windward shore (i.e., $3.58\ \mathrm{mm \cdot d^{-1}}$), or the 12 stations downwind from the KMR (i.e., $3.3\ \mathrm{mm \cdot d^{-1}}$), as shown in Fig. 5. Also, the rainfall on the AOR days at and near the windward base of the KMR (stations 837, 886.7, 839.7, 839, 839.3, 788, and 787.1) is almost 8 times the coastal rainfall.

If we argue that the initiation of the rain-formation process in the Sc occurs at the time the clouds pass over the windward shoreline, then the increase in precipitation over the island should be a function of distance from the shore, assuming winds of equal speed over the island. We observe, however, that the increase is more abrupt over the northwest half of the KMR (see Fig. 9). This difference in rainfall amount is attributed to the presence of rugged precipitous mountain terrain nearer the coastline north of line AB (Fig. 5). A similar difference in rain amount is also reflected in the crowding of the isohyetal lines on the annual precipitation maps of this area of Oahu (Taliaferro, 1959).

Thus it appears that the mountains are almost immediately effective in causing greater rainfall in the Sc cloud stream, and the rapid increase in shower number with distance inland (e.g., see Fig. 4) shows that greater rainfall cannot be due simply to augmentation of showers already falling as the clouds pass over the shoreline. It should be noted that stations 837, 839.7, 839.3, and 787.1, which are deep within windward mountain valleys, frequently record high rainfall and long durations (see Table I). This is thought to be due to the orographic effects of the mountainous headlands which extend from 1 to 2 km to windward of the stations.

It seems evident that under average wind speeds raindrops can form in and fall from these oceanic Sc clouds in from 13 to 26 min, producing a continuous rain of 1 to 8 mm·h^{-1} at many or all of the KMR gages. For the showers falling at the windward mountain-valley stations under these conditions, the average apparent rain-formation times become 10 min, with a minimum of 7 min for the gage closest to the windward shore (~3.5 km). All of these times are markedly less than those estimated by calculation and measurement by Saunders (1965) and Moore (1974).

It should be pointed out that the estimates given by Saunders and by Moore include the times required for the major vertical growth of the cumuli up to the time rain was observed within the clouds by radar. In our case the Sc overcast producing the orographic rains preexisted long before the wind stream carried them over Oahu, with no evidence of a marked additional vertical development of the Sc clouds upon encountering the island. Leopold (1949) and Mordy and Eber (1954) have both noted this absence of marked growth of wind-borne cumuli over the KMR and attributed it to the suppressing effects of the temperature inversion so often present in the lower atmosphere. Thus the major changes occurring within the Sc clouds due to passage over the island are probably the speed and directional shears, the turbulence introduced in the lower layers, and the upward deflection of the moist subcloud air during passage over the KMR.

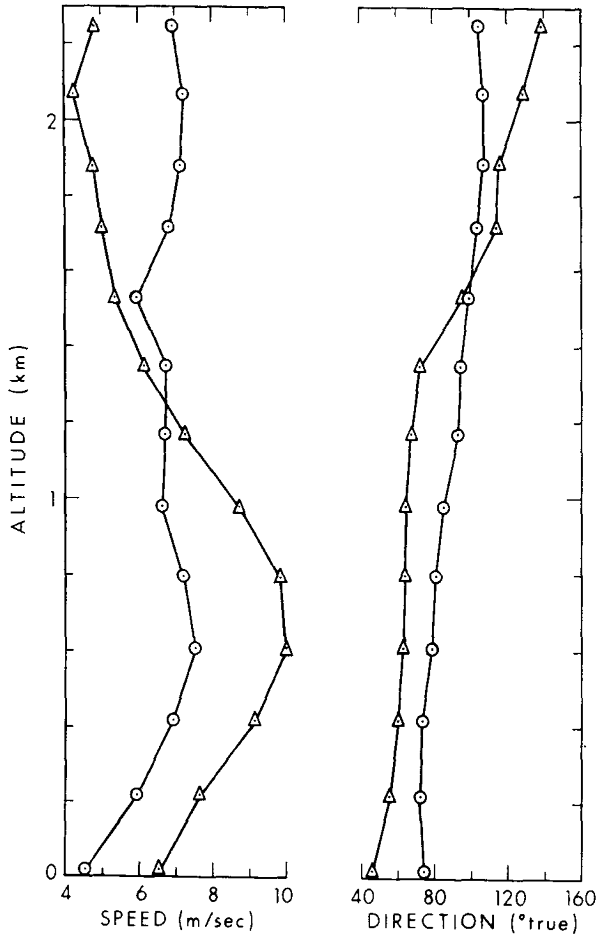

Fig. 8. Mean wind velocities in the lower atmosphere over Honolulu during the AOR days (triangles) compared to winds during a comparable period of TOS days (circles). Note the greater veering and speed changes with height during the AOR days.

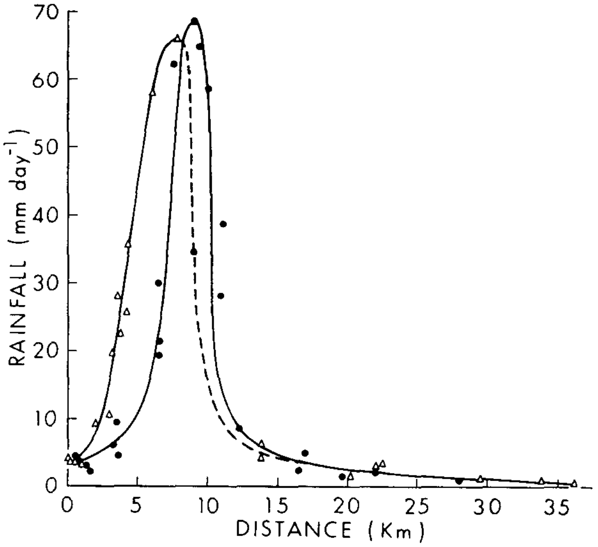

Fig. 9. Diagram showing the mean rainfall amounts on all of the AOR days, as a function of station distance from the east-northeast shore line. The triangles represent stations north of line AB (Fig. 5); circles, the stations south of the line. See text.

One may argue, as indicated earlier and below, that the presence of the island may be "felt" by the lower air stream upwind of Oahu, thus perhaps producing rain-initiating disturbances within the Sc clouds before the air stream arrives over the windward shore. Such disturbances would of course increase the apparent time required for rain to form in and to fall from the Sc clouds.

Siler (1964) made observations of the surface flow of trade winds over Oahu, from which he tentatively concluded that the wind field over the mid-portion of the windward side of Oahu was "undergoing speed convergence," and that this convergence might explain the high rainfall observed at the windward bases of the KMR. A comparison of the winds at stations K and B (see Fig. 1) with those observed by ships at sea on the AOR days also supports Siler's suggestion of a speed convergence on the windward side of the island.

On the other hand, Yeh *et al.* (1951) have noted a divergence on the windward side of Oahu, due to a flow of part of the wind stream through the Kauai and Kaiwi Channels between the islands. Leopold (1949) also indicated a similar divergence in the tradewind stream about the windward side of parts of the islands of Maui and Hawaii, based upon observations of the motion of cumulus cloud bases.

An additional windward effect, caused by island heating (Malkus, 1955), sometimes called the subsidence ring phenomenon, should be considered. The extent to which this effect occurs seaward of Oahu is uncertain. However, a recent Gemini color photograph shows an example of a cloudfree ring seaward of the island of Hawaii (NASA, 1967; p. 200). Both of these phenomena (i.e., divergence and subsidence), when occurring windward of Oahu, would tend to suppress cloud growth, thus acting in the opposite sense to the speed convergence suggested by Siler's work.

Until more information is available on this question of the modification of the wind stream northeast of Oahu, it seems reasonable to use the windward shoreline as the beginning point in estimating island orographic effects in starting precipitation processes in clouds passing from sea to land. At present, of course, we have no proof that an island effect in initiating rain in the Sc clouds does not actually occur over the sea upwind of Oahu.

If encountering the island is the basic cause of the formation of the AOR in the Sc cloud, it is puzzling why rains falling on the windward side of the KMR are generally showers, whereas, after passage over the mountain barrier, rains falling are continuous. This difference in the nature of the rains on the two sides of the KMR suggests that the role of the island-produced disturbance in the Sc clouds is itself different on these two sides. It appears that the turbulence in the cloud stream and the upward deflection of the subcloud air due to passage over the long 600 m high mountain barrier actually triggers the total rainout of these clouds (see Figs. 2 and 5), whereas the milder disturbance by the less rugged terrain of much of the windward-island surface largely induces showers.

On one of the AOR days (25 March 1969) I drove an automobile back and forth through Wilson Tunnel, which cuts through the KMR (see location T, Fig. 1). My purpose was to observe repeatedly the absence of rain on the windward side from a site (elevation ~90 m) near the northeast end of the tunnel and, upon turning back through the tunnel and downwind, to measure the distance (~1.7 km) to the point on the leeward roadway where the Sc rainout began. Continuous rainfall occurred for about 5 km beyond this point, followed by complete evaporation of the remaining cloud material. These observations were made between 1040 and 1150 LST, when rain was falling continuously at all of the leeward KMR rain recorders (i.e., stations 718, 716, 734, 782, 777, 883.12, and 882.4), and none was seen or recorded at windward coastal stations (724.7, 791.3, 905.2, and 912). Upon returning to Honolulu immediately after this experiment, I noted that the appearance of the Sc cloud and rain over the KMR was typical AOR, as pictured in Fig. 2.

The absence of rain between the northeastern end of the tunnel and the windward shore during the experiment suggests that the mountain ridge is causing the rain to form. If the AOR is forming exclusively as a result of cloud stream passage over the precipitous KMR, one concludes from the mean winds at cloud level on that day, and from the distances measured, that the rain was produced in the Sc clouds and fell out of them in a minimum of ~6 min. The location where the first rain fell on the highway was at an elevation about 300 m below cloudbase altitude. The largest drops were about 1 mm in diameter and fell from cloud base in about 1 min leaving only ~5 min for drop growth in the cloud. Recent experiments by Jonas and Goldsmith (1972) have shown that wind shear greatly increases small droplet collection efficiencies. Can it be that wind shear causes 1-mm diameter raindrops to grow from cloud droplets by the collision-coalescence process in so short a time? Radar precipitation studies are needed in this location during AOR to clearly determine where raindrops first appear in these marine Sc clouds.

4. Conclusions

Extensive shallow layers of warm wind-borne Sc clouds, apparently containing little or no rain while over the sea, produce continuous relatively constant low-intensity rains shortly after encountering the precipitous KMR of Oahu. Estimates of the time required for rain to form in these clouds, assuming the onset of rain generation to coincide with cloud arrival over the windward shore, reveal intervals much shorter than those previously reported for oceanic cumuli. Alternatively, following the time limitations estimated from earlier work in trade wind cumulus, we are led to conclude that an island effect upon the AOR generation processes in Sc clouds may begin over the sea many kilometers upwind of Oahu. At present the weight of evidence is against this alternative, so we return to the idea that an unusually rapid rain-generation process is occurring in the Sc clouds over Oahu. Since marked growth of the Sc clouds does not occur over Oahu, the major remaining causative factors producing the AOR are thought to be the shear, turbulence, and additional moist air introduced in the cloud stream by the island.

Acknowledgments. J. C. Sadler and R. C. Taylor of the Meteorology Department, University of Hawaii, and W. Taliaferro of the National Weather Service, Honolulu, aided this study in numerous ways. Staff members of the U. S. Geological Survey, the Honolulu Board of Water Supply, the Hawaiian Sugar Planters Association, and the Hawaii Water Authority supplied many rainfall records. Other weather records were contributed by the National Weather Service, Honolulu Airport, and the Weather Service, Marine Corps Air Station, Kaneohe. Dr. R. R. Hoyer, former graduate student at the University of Hawaii, assembled much of the preliminary weather-satellite and rainfall data, and Mrs. Ethel McAfee, of the publications department, made suggestions for improving the text. Helpful criticisms of this paper by Saul Price of the National Weather Service, Honolulu, and by D. C. Blanchard and J. E. Jiusto of New York University in Albany are appreciated.

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