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Woods Hole, Massachusetts

<u>Reference No. 52-99</u>

Raindrop Size Distribution and Associated Phenomena in Hawaiian Rains

By

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Technical Report No. 4
Submitted to Geophysics Branch, Office of Naval Research
Under Contract Nonr-798(00)(NR-085-001)

December 1952

APPROVED FOR DISTRIBUTION ______________
Director

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Abstract

A brief survey of the major techniques of raindrop size sampling is given. The filter paper technique, finally adopted for use in this study, adapts itself admirably to the sampling of Hawaiian orographic rains.

The change in the drop size distribution of rain as it falls from cloud to ground may be considerable. It is effected by wind shear, gravity separation, evaporation and drop collision. The evaporation error alone can be appreciable. The many small drops of the Hawaiian orographic rains may completely evaporate in a sub-cloud fall of only 1000 meters. The evaporation problem was eliminated and the others minimized by sampling all the orographic rain at cloud base or within the cloud itself.

Drop size distributions were obtained in such non-orographic rains as thunderstorms and cyclonic storms. The pertinent meteorological factors such as liquid water content W, median drop diameter, and radar reflectivity Z agree reasonably well with the values given by other investigators.

The measurements made in orographic rains, however, lead to considerably lower values of these factors. The raindrop distributions are narrow with the largest drops rarely exceeding 2 mm. diameter.

Concentrations of drops <0.5 mm diameter often are in excess of $40{,}000\ m^{-3}$. These large numbers of small drops give low values for median drop diameter and radar reflectivity but high values of liquid water content.

Variations in these parameters were found to exist at the same location over a period of several days. Differences were found in a single cloud system by sampling at different elevations within the cloud.

1. Introduction

> "Our knowledge in regard to the mechanism of rain formation, i.e., the precise manner in which the nucleus of each raindrop is organized and the method by which the aqueous material is added to the nucleus during its growth, so that eventually raindrops of considerable size are produced, has hitherto been very unsatisfactory. Equally so is our knowledge of the actual altitudes within the clouds at which various rainfalls originate, the relative quantities of rain precipitated from different clouds and storms, the dimensions of the individual raindrops, and their variation in different storms and in different segments of the same storm."

These words are from the opening paragraph of a paper written at the turn of the century by Wilson A. Bentley (1904), one of America's first experimental meteorologists. Bentley's remarks on the state of knowledge of the fundamental processes of the formation of rain are, in many cases, nearly as applicable today as they were fifty years ago. Indeed, it was only recently that the impetus was received for extensive investigations on the general subject of the formation of rain and snow (Schaefer, 1946).

In October 1951, the writer and Mr. A. H. Woodcock, both from the Woods Hole Oceanographic Institution, went to the Hawaiian Islands to begin a ten month study with the Meteorology Department, Pineapple Research Institute and Hawaiian Sugar Planters Association. The study was aimed toward a better understanding of the basic mechanism of warm cloud rain. It is believed that large salt particles of marine origin form the nuclei from which raindrops develop, first by condensation and later by accretion (Woodcock, 1952). To further test this hypothesis, three separate programs of study were carried out: (1) Measurements were made of the air-borne salt particle distribution at ground, sub-cloud, and cloud level; (2) The variation of rainwater chloride content vs. intensity was studied; (3) The raindrop size distributions at various points within the cloud were obtained. The studies made in connection with this third program are the source of data for this paper.

One of the earliest papers on raindrop size described observations of splash pattern on slates (Lowe, 1892). At about this time the idea of exposing chemically treated filter paper to the rain was suggested, but it remained for Wiesner (1895) to publish the first detailed results. A novel and new approach to raindrop size measurements was achieved with the flour technique (Bentley, 1904). The raindrops, on falling into a flour filled container, produced hard dough pellets whose size was a function of the diameter of the original raindrops. This method has subsequently been used by several investigators (Laws and Parsons, 1943; Chapman, 1948; Blanchard, 1949a). An account of European investigations of raindrop size and accompanying instrumentation prior to 1942 can be found in an excellent survey paper by Neuberger (1942).

In an effort to develop a drop size measuring technique which would eliminate the splashing and spreading of the large drops on contact with the sampling surface, the writer (Blanchard, 1949b) experimented with soot-coated 100 and 50 mesh brass screens. Raindrops, in passing through the screen, removed a circular area of soot whose diameter was a function of drop size. This method was considerably improved when nylon screens were substituted for wire screens (Mt. Washington Observatory, 1951a). The nylon screens were treated with a benzin-lanolin solution and then covered with powdered sugar. In this manner some excellent raindrop samples have been obtained. Mr. A. H. Woodcock recently attempted to use these screens from aircraft flying at speeds of 60-80 mph. With low speeds and low relative humidities a drop size distribution can be obtained but in the high humidity region near cloud base and within the rain area the hydroscopic sugar particles absorb water and render the screen useless. It would appear, from some brief experiments in sooting nylon screens, that the hydrophillic soot particles from acetylene smoke would serve in lieu of powdered sugar for measurements of drop size from aircraft.

Electronic techniques have been developed in an attempt to obtain continuous measurements of drop size in flight. Cooper (1951) has used a balloon-borne instrument for telemetering raindrop size. An instrument, similar in principle, has been used in France (Maulard, 1951). In the United States a number of reports, dealing with both optical and momentum devices, have been issued on air-borne instrumentation*. At the time of this writing few of these instruments have been put into use.

In Australia a raindrop spectrograph has been used to obtain continuous drop size measurements at the ground (Bowen and Davidson, 1951). This ingenious and relatively simple technique permits a direct determination of raindrop size.

2. Hawaiian climate

As any study of this type should be made with cognizance of the influence of the local topographical and meteorological conditions, a brief discussion of these factors and their influence on Hawaiian rainfall will be given.

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* The latest work on such devices may be found in the proceedings of the Third Radar Weather Conference, McGill University, Montreal, 15-17 September 1952.

The eight Hawaiian Islands, some 2400 miles southwest of San Francisco, are oriented northwest-southeast and extend from a latitude of 19° to 22° North. The entire island chain is located within the Pacific northeast trades. These trades are characterized by a temperature inversion with a modal elevation of 6000 feet. Below the inversion the air is moist and turbulent with an average lapse rate of 8.3 C per 1000 m. As one passes up through the inversion the air becomes quite dry and free from turbulence. The usual convective and orographic clouds are normally limited by the inversion. It is only on the relatively infrequent occasions when the trade winds are weak or subside completely that the clouds remain over the islands for a sufficient time to convectively build up to high altitudes. As these conditions are so infrequent it has proved difficult to properly evaluate the results of dry ice seeding in Hawaii (Leopold and Mordy, 1951).

A marked departure from the normal trade wind weather is introduced by the passage of easterly waves in the trade wind current and by the Kona storm (Simpson, 1952). The Kona storms, occurring perhaps 2-3 times during the winter and spring, are cyclonic storms which develop to the northwest of Hawaii. During the day or two of Kona-type weather heavy rainfall is experienced throughout the islands.

The topography of the islands is the major factor in the formation of the orographic clouds. This is effectively shown in the isohyets of the annual rainfall, especially those of the island of Hawaii (see Fig. 1). Strong isohytal gradients are set up in critical areas of trade wind flow. For example, note the marked increase in annual rainfall from sea level to a point some 10 miles up the east flank of Mauna Kea. In this distance the annual rainfall increases by 250 inches. A rapid decrease of annual rainfall with altitude is found at higher elevations. An explanation for this rainfall maximum has been given by Leopold (1949), who attributes it to the splitting of the trade winds by the huge volcanic cones. He states, "Streamlines drawn in accordance with the observed splitting of the trades by each of the two cones, Mauna Loa and Mauna Kea, would converge directly over the observed zone of greatest rainfall."

3. Measurements of drop size distribution

Prior to the field experiments, provision was made to obtain drop size measurements both with nylon screens and with chemically treated filter papers. In view of the difficulties encountered with the screens at high humidities plus the fact that a low power microscope is essential for accurate determination of the drop size the filter paper method was adopted. An

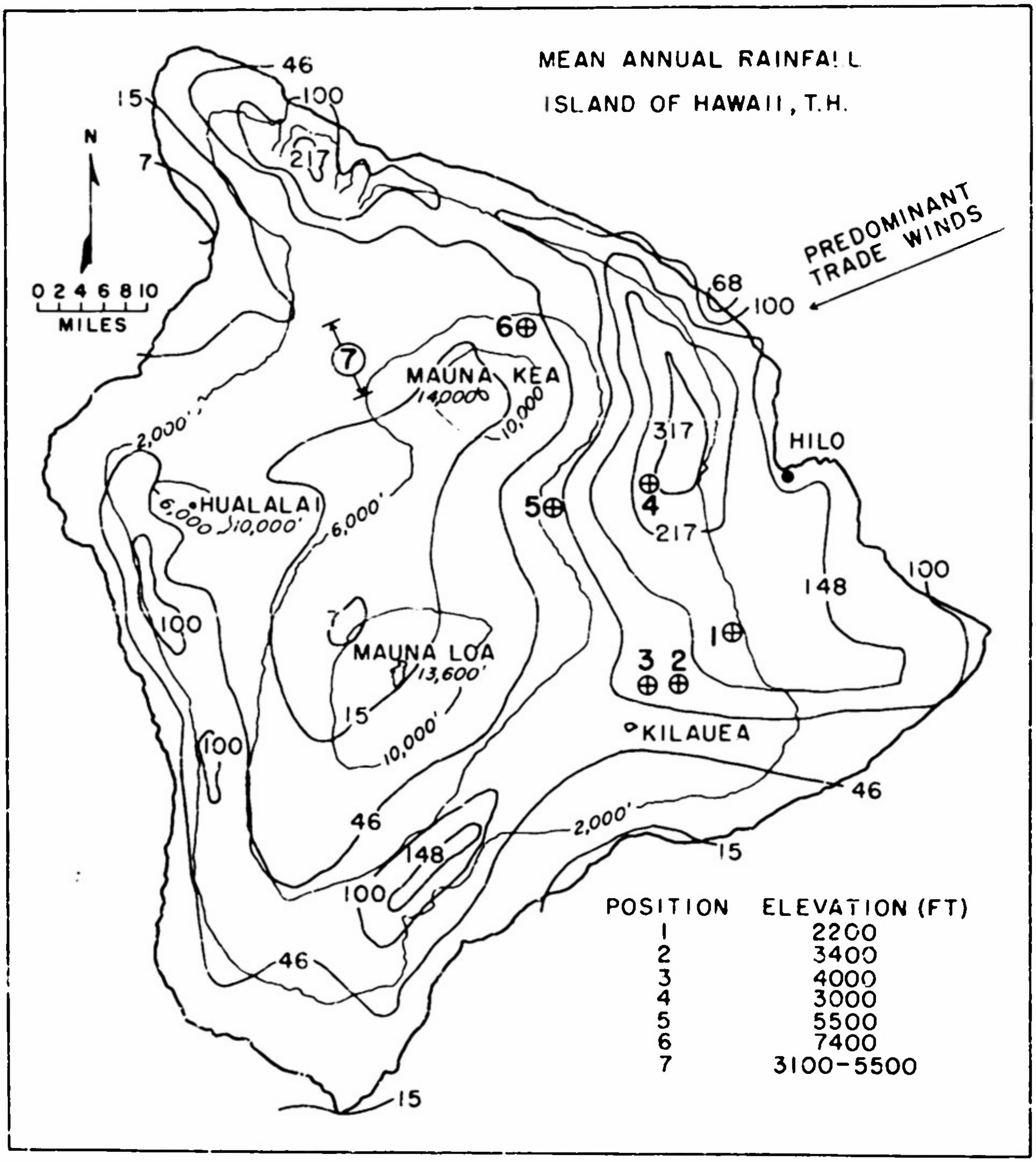

Fig. 1 Isohytal map of the island of Hawaii, T. H., with the locations of the seven sampling positions.

objection to using filter papers is that the papers are sentitive to changes in relative humidity (Niederdorfer, 1932). The writer found that this was especially true at R.H. > 70. Inasmuch as the measurements of drop sizes carried out in this study were usually made at some point within the cloud it became necessary to store the filter papers in such a manner as to keep the R.H. < 70. This was accomplished by storing the papers in a vertical position, 6 mm apart, in a box containing several desiccating bags. Some 40 papers could be stored in this manner.

Whatman #1 filter papers, dusted with methylene blue dye, were held between two brass rings. These were exposed to the rain, with the aid of a small aluminum cover and a stopwatch, for any desired period of time. The exposure times, filter number, time of day, and other pertinent meteorological information were recorded with pencil on painted metal strips. Data were recorded in this manner in heavy rain and cloud without any smearing whatever.

With the aid of a calibrated scale raindrop sizes were read, in 0.2 mm intervals, directly from the filter papers. This scale was designed from a calibration curve constructed from data obtained with water drops of known size at terminal velocity. The calculation of the space distribution of the drop sizes, N_D (m^{-3} 0.2 mm^{-1}), from the filter paper distribution involves a knowledge of the effective filter paper area (252 cm^2), time of exposure, drop count in each 0.2 mm size interval, and a representative terminal velocity for the drops within each size interval. The terminal velocities used in this work were those experimentally determined by Gunn and Kinzer (1949). A rapid rate of change of terminal velocity with drop diameter is encountered with drops < 0.2 mm diameter*. For this reason all computations of N_D for drops < 0.2 mm are subject to error. The mass of water represented by these drops is negligibly small when compared to the total. Therefore, computations of liquid water content W and radar reflectivity Z are, in most cases, little effected.

The intensity of rainfall R(mm hr^{-1}) was computed from the filter paper drop distribution. Within each 0.2 mm interval an average mass (mg) was determined. This average mass multiplied by the drop count in that particular interval defined its contribution to the intensity. The writer realizes that such a method of determining intensities may be subject to error when the drop distributions containing large drops (> 3 mm) are

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* Unless otherwise noted, all drop sizes in this paper will be understood to be in mm diameter.

considered. Here the distribution of drops arriving at a horizontal surface is usually skewed, with a long tapering tail reaching into the region of large drops. In this region the distribution is often statistically inadequate and, as these large drops represent the majority of the water, incorrect intensities are computed. This is not the case, however, with the orographic rain of Hawaii. The drop size distributions have low standard deviations with the largest drops seldom exceeding 2 mm.

The intensities computed from filter papers have been found to agree reasonably well with those obtained with an 80 cm diameter stainless steel funnel (see Fig. 2). With the aid of a plywood cover and two flexible automobile windshield wipers, both mounted to rotate around the inner surface of the funnel, sufficient water for intensity calculations could be collected in 10 to 200 seconds. On several occasions two such funnels were used at the same location. The results were, as expected, nearly identical. As shown in Figure 2, the average intensities as computed from funnel measurements vary considerably. The near instantaneous intensities computed from filter papers follow this trend probably as well as can be expected.

4. Changes in drop size distribution in passage through the sub-cloud layer

It appears that most, if not all, of the raindrop size measurements reported in the literature were made at a considerable distance below cloud level. The changes in the spacial distribution of drops as they fall in the sub-cloud air can be considerable depending upon the fall distance, temperature and relative humidity, relative drop sizes, and wind shear. These effects were recognized many years ago (Bentley, 1904) but received little attention as few measurements were then being made of raindrop sizes. The measurements reported in this paper, with the exception of those made in the thunderstorm and Kona storm (Samples 14-30 of Table 1) were obtained either at cloud base or at some point within the cloud system. This was made possible by roads which led up to elevations of 10,000 feet on both Mauna Kea and Mauna Loa.

The effects of drop size distribution by the above-mentioned factors will be briefly discussed.

(a) Wind shear and relative fall velocities

If we at first consider the oversimplified case of zero shear it becomes apparent that, due to the relative fall velocities alone, large changes may occur in a spacial drop distribution between cloud and ground level. For example, consider a

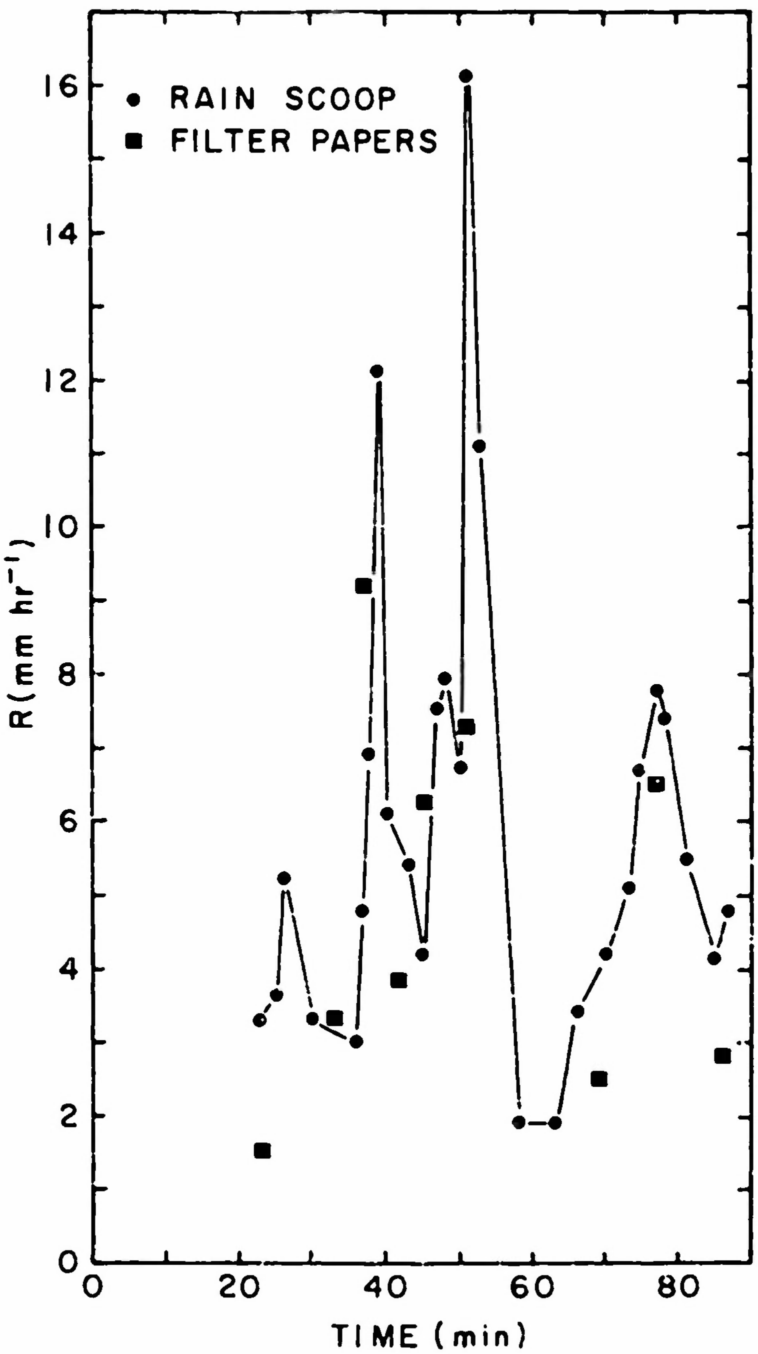

Fig. 2 A comparison of the determination of rain intensity from filter papers and the 80 cm. diameter "rain scoop".

distribution at cloud level to contain drops ranging in size from 0.2 to 4 mm. With a cloud to ground distance of 2000 m the 0.2 mm drops would arrive at the ground some 40 minutes after the 4 mm drops with the intermediate drops arriving at successively earlier times. At ground level the distribution would be transient, not reaching the steady state until 40 minutes after the arrival of the largest drops. At the onset of natural rains it is often observed that large drops precede the smaller ones by several minutes but seldom by times exceeding 10 minutes. This would suggest that either the drops originated at different times or positions within the cloud or that small drops evolved as a result of continual growth and breakup of the larger drops.

If we now consider the usual case in which horizontal winds increase with altitude the problem becomes quite complex. It is apparent that in order to have drops of several sizes arriving simultaneously at a given point on the ground it is necessary that the large and small drops originate at different levels within the cloud or else originate at the same level with the smallest drops forming first. Both of these explanations have been considered, with the former tentatively accepted, as one explanation of observed drop distribution at the beginning stages of a shower (Atlas and Planck, 1952). However, regardless of which explanation is used it requires that the large and small drops constituting the ground sample have their origin at different locations within the cloud.

(b) Evaporation of raindrops

Recent experimental work (Kinzer and Gunn, 1951) on the evaporation of falling water drops has resulted in a table of evaporation rates, at several relative humidities, for drops of various diameters. The writer has expressed this table in functional form and combined it with an expression relating terminal velocity to drop diameter. The resulting differential equation was integrated to obtain an equation relating drop size and distance fallen. At a R.H. = 90 and an isothermal atmosphere of 20°C. it was found that small drops can completely evaporate in a fall of about 1000 m. For example, a 1.5 mm drop will evaporate to only 1.42 mm in a fall of 2000 m while a 0.5 mm drop will evaporate completely in a little over 1000 m. It is interesting to note that these calculations agree relatively well with the more detailed theoretical calculations of Best (1952).

The calculations indicate that large changes in the drop size distribution are to be expected amongst the smallest drops. The evaporation of the small drops is serious in that it deprives us of any knowledge of their distribution. This knowledge is extremely vital to the question of the mechanism of rain formation, as these drops represent the great majority of the total drops present. The great difference in numbers of small drops in rains from freezing and non-freezing clouds is pointed out later in the paper.

(c) Drop collision in the sub-cloud layer

As a direct consequence of the differences in fall velocities of the various sized drops it is to be expected that raindrop collisions in the sub-cloud layer will tend to modify the distribution which existed at cloud base. Calculations of these effects plus those of evaporation have been made by Rigby and Marshall (1952). They find that the collision effect tends to increase the number for large drops while decreasing it for the small ones. Evaporation effects, on the other hand, will tend to decrease the distribution at all sizes. On combining both evaporation and collision effects they found that the change in distribution for the larger drops was not as pronounced as that caused by collision effects alone. The distribution of the small drops, which was decreased by both collision and evaporation, naturally departed even more from its initial state when both effects were considered. The general conclusion arrived at by Rigby and Marshall was that the basic form of the drop size distribution would not be seriously effected by any of the aforementioned factors. It might be added that their work was based on distributions which extended into drops of 3 mm. As a majority of the drop distributions of orographic rain from warm clouds have 50 per cent of the water contained in drops <1 mm it is to be expected that evaporation effects would be quite pronounced. In fact, the occurrence of virga, the result of evaporation, is a most common event associated with the warm clouds of Hawaii.

5. Raindrop size distributions from clouds extending above the freezing level

On three different occasions drop size samples were obtained in rains whose origins most likely were associated with ice crystal formation.

(a) Windward Mauna Kea

On 27 March 1952 raindrop measurements were taken on the northeast flank of Mauna Kea at an elevation of 7500 feet. These are represented by distributions #1-13 of Table 1. At 0630 the weather was a follows: winds light and downslope, temperature 6.3 C and a light drizzle falling from an overcast which was solid only near the moutain. At about 0840 both the drizzle and the wind increased in intensity. Sample #2 of Table 1, as compared with #1, shows the change in the nature of the drop distribution*. The absence of any drops over 1 mm and the large numbers of drops <0.5 mm in sample 1 are typical of the distributions from non-freezing clouds. (See samples 31-113). The sudden increase in maximum drop size and corresponding decrease in small drops, as indicated by sample 2, was shown by all subsequent measurements until 1412 and sample 10. The change in distribution of sample 10 was no doubt associated with a wind shift to east at 1400 plus a lowering of cloud base 100 feet or more to the sampling position. At 1700 the winds became very irregular and strong. The rain continued until about 2100. At sunrise on March 28 it was observed that all of Mauna Kea above the 10,000 foot level was covered with snow. It was then realized that the rain of the previous day had probably originated as snow.

The pronounced change in drop distribution from sample 1 to sample 2 was accompanied by a marked change in the chloride content of the rain. Chloride determinations on five rain water samples taken between 0730 and 0842 showed the expected trend towards an inverse relationship between rain intensity and chloride content (Woodcock, 1952). During this time the chloride concentration dropped from 20 to 0.4 ppm. From 0842 through 1802 twenty rain water samples were obtained. Although the samples were obtained in intensities ranging from 1.6 to 13 mm hr^{-1} the chloride concentration was never above 0.3 ppm. Rain from the typical Hawaiian orographic cloud usually has clorides present in amounts from 2-50 ppm. The small amounts found above indicate that relatively salt free high level air and not orographically lifted salt laden air was responsible for the precipitation.

(b) The Kona storm**

Heavy and continuous rain fell throughout the day of 19 January 1952. For a period of some 20 hours the weather was entirely dominated by a Kona or cyclonic storm. From 1031 through 1533 samples 14-22 were obtained at the Pineapple Research Institute, Honolulu, T. H. The cloud base was estimated at 200 feet. The temperature at 1200 was 20.7 C with a wet bulb depression of 0.4 C. The winds were light with occasional strong gusts.

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* Hereafter in the paper all reference to Table 1 will be in terms of the sample number only.

** Kona is the Hawaiian word for leeward. A kona storm approaches from the leeward side of the islands, with respect to the trade winds, hence its name.

The drop size measurements covered a wide range of intensities, ranging from 1.8 to 127 mm hr^{-1}. A few minutes after sample 18 was taken the intensity rose from 127 to 242 mm hr^{-1}. This latter measurement was made with the 80 cm diameter funnel.

(c) The thunderstorm

On 11 February 1952 weak trade winds were indirectly responsible for the formation of convection cumulus over the island of Oahu, T. H. By 1300, large cumulus were forming over the city of Honolulu. Extreme vertical depth was suggested by the intense darkening of the cloud base. The first rain fell at 1352 and continued on for about 35 minutes. During that time, sporadic thunder was heard and small hail pellets were reported*.

Eight drop size measurements (samples 23-30) were obtained. With the exception of the first 3 measurements the drop distribution was, in general, similar to that found in the Kona storm. Sample 23, obtained 2 minutes after the start of the rain, contained no drops $<$ 0.8 mm. A minute later at 1355, a few drops in the 0.5 mm range had arrived. At 1356 drops as small as 0.4 mm were present, although in small numbers. From 1401 on, all samples indicated the existence of drops $<$ 0.2 mm.

The drop distributions of Figure 3 show the gradual increase of small drops with time. The two dashed lines are the distribution functions of the Laws and Parsons (1943) data, as presented by Marshall and Palmer (1948), for intensities of 25 and 1 mm hr^{-1}. Note how the transient is characterized by a negative slope, becoming increasingly positive with time. Sample 26 (R = 8.8 mm), the first to contain drops $<$ 0.4 mm, is the first distribution that has a pronounced positive slope.

An explanation for this behavior is beset with many criticisms, arising mainly from a lack of knowledge of the drop distribution at cloud base. With an estimated cloud to ground distance of 1000 m and a distribution of drops of all sizes simultaneously starting their fall from cloud base it is evident that the slower falling smaller drops will reach the ground some time after the large ones. Approximately 3 minutes will elapse between the arrival of drops $>$ 2.4 mm and those of 0.8 mm. It is to be noted that sample 23, taken two minutes after the beginning of the rain, contains no drops $<$ 0.8 mm. Subsequent samples, obtained 3 or more minutes after the initial rain, contain increasing numbers of drops $<$ 0.8 mm. Thus, the time of appearance of the 0.8 mm drops agrees with the

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* According to newspaper reports, hail was reported several miles from the sampling position.

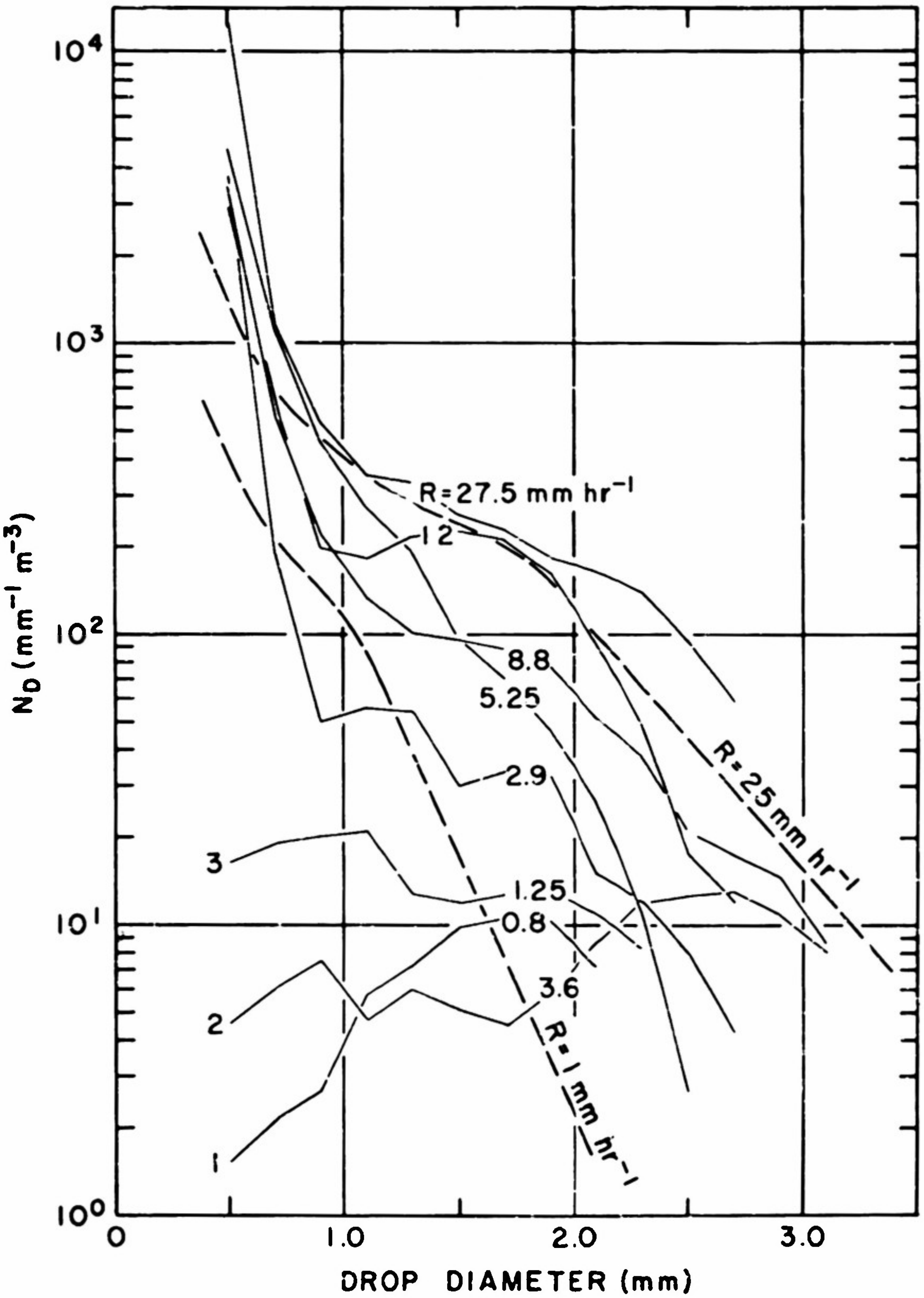

Fig. 3 The distribution function (solid lines) of the thunderstorm data (Samples 23-30). The dashed lines represent the smoothed distribution functions of the Laws and Parsons data. The numbers in the lower left hand corner indicate the three transient distributions in a chronological order.

estimated time of 3 minutes. On the other hand, the drops < 0.2 mm should not appear until some 21 minutes after the initial rain. Clearly this is not the case. It is most likely that the large and small drops had their origin at different altitudes or at the same altitude but at different times (see section 4a). The other alternative is that smaller drops are being produced by drop disintegrations resulting from collisions and turbulence (Blanchard, 1950).

6. Liquid water content as a measure of the drop distribution

It is not always convenient to compare two sets of rain measurements by comparing their drop size distributions. It would be far more desirable to represent a drop size distribution graphically by a single point. Of course, such a representation would tell nothing of the total drop count m^{-3} but it could indicate whether the distribution had a large or narrow spread.

This is essentially what is measured by the liquid water content W (mg m^{-3}). For example, let us consider the hypothetical distribution of 1 drop m^{-3}. This defines an intensity R and a liquid water content W. Let this drop be split into two equal sized smaller drops. Although the liquid water content is unchanged, the slower falling smaller drops lower the intensity. One or more of these smaller drops will, therefore, have to be added to attain the original intensity. It is apparent that this process can be repeated indefinitely. At each sequence the intensity is held constant by adding drops, the liquid water content rises, and the drop distribution tends toward smaller and more numerous drops.

The liquid water contents of the drop size distributions of the three storms represented by samples 1-30 are shown in Figure 4 as a function of the intensity R. The dashed line is the locus $W = 67R^{0.84}$ (Best, 1950), representing the mean value of data obtained by other investigators. With the exception of six points the present data agrees reasonably well with this locus. Note that the three drop distributions from the windward Mauna Kea rain representing intensities < 2 mm hr^{-1} have liquid water contents considerably higher than the locus would suggest. This, of course, implies a drop distribution of relatively small spread and numerous drops. Reference to samples 1, 10, and 11 show that this is the case. In each of those samples, from 7000 to 17,000 drops m^{-3} are < 0.4 mm. The spread in drop distribution is about half that of the other samples.

The three anomalous thunderstorm samples indicate the opposite trend; that of a wide distribution coupled with a

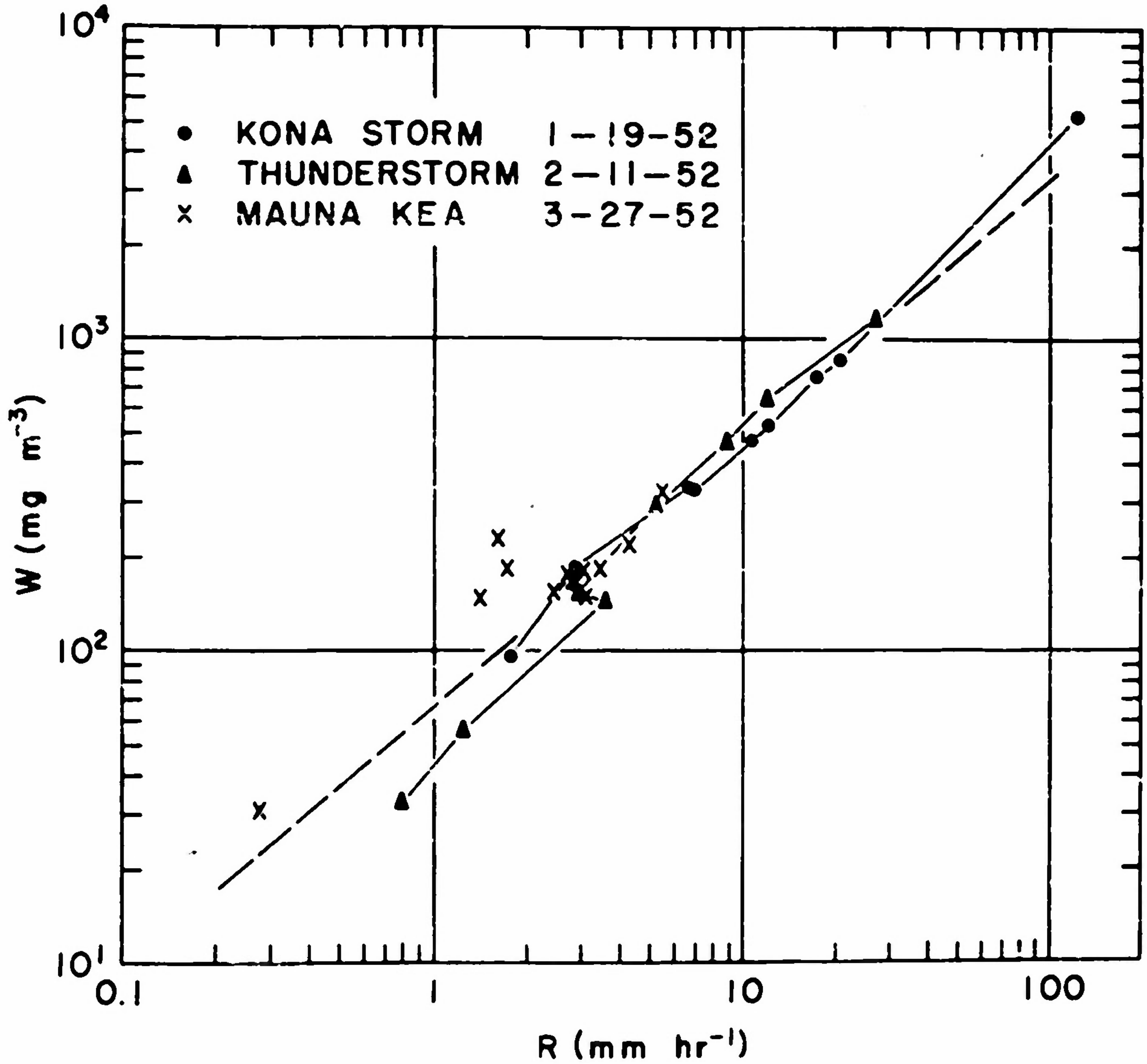

Fig. 4 Liquid water content W as a function of rain intensity R for samples 23-30. The dashed line is the locus obtained by Best (1950). The lines connecting the points are visual aids only.

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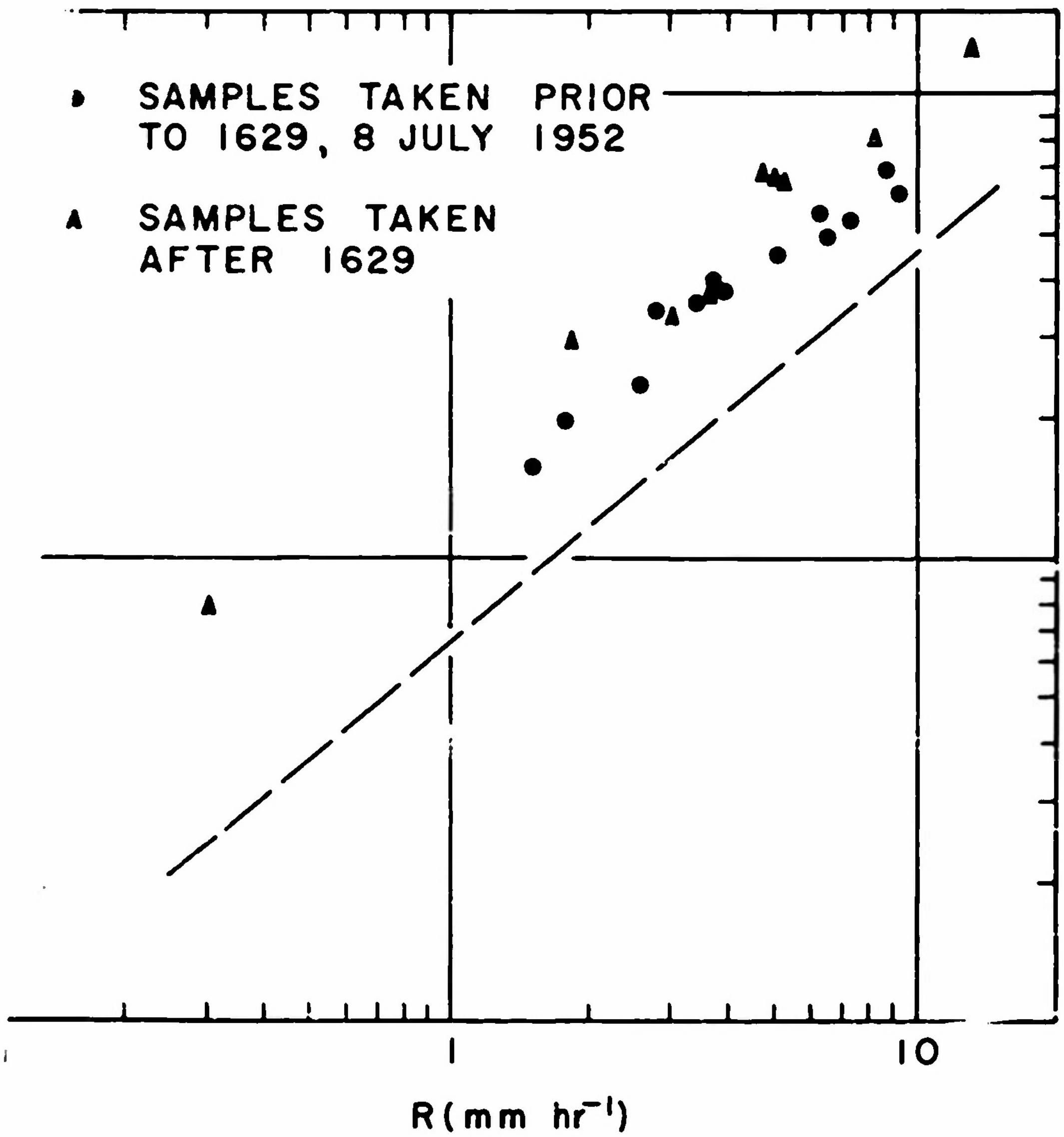

ƺ. 5 W vs. R relationship for samples 31-52. The dashed line is the locus obtained by Best (1950).

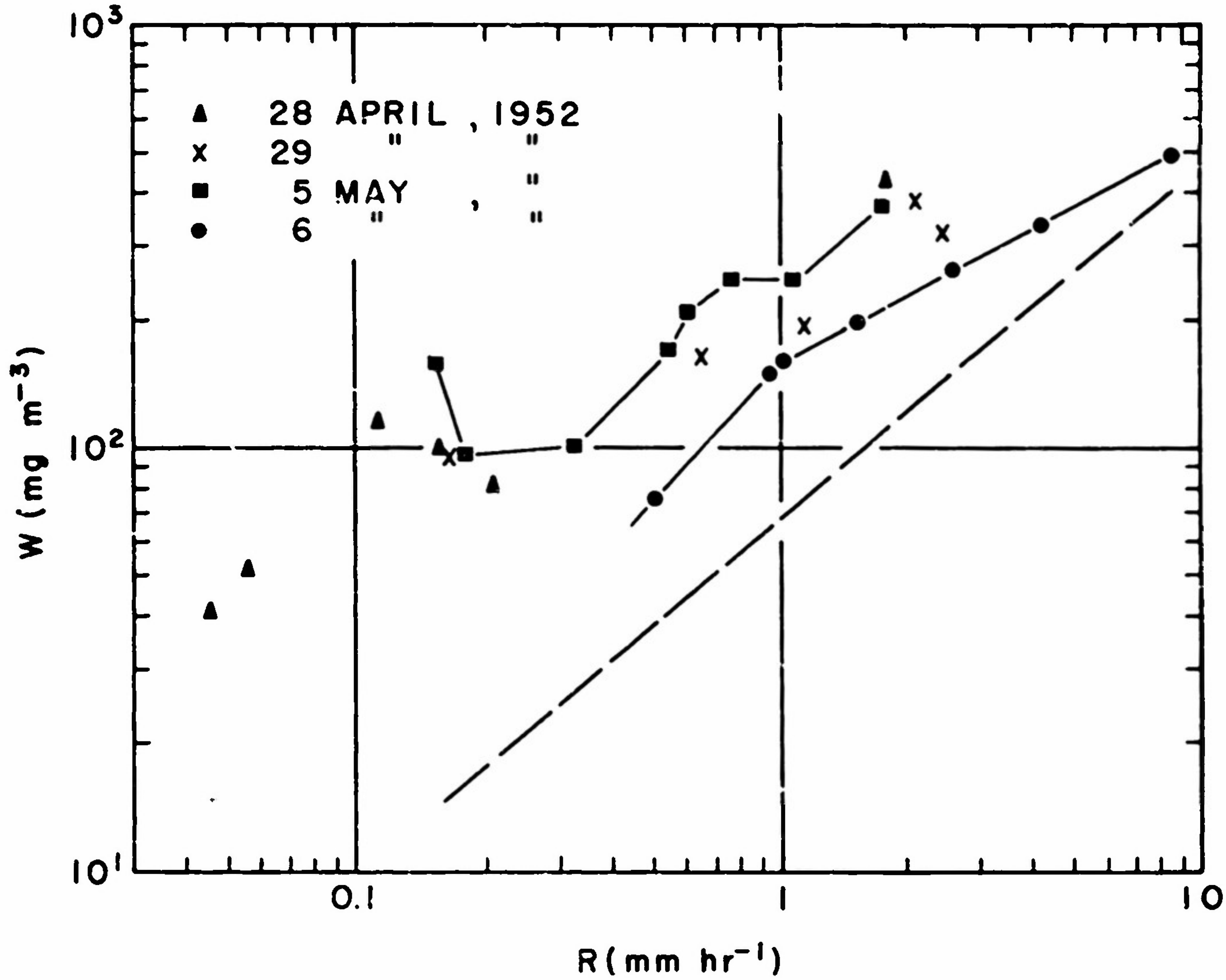

Fig. 6 W vs. R relationship for samples 53-78. The dashed line is the locus obtained by Best (1950). The lines connecting the points are visual aids only.

Samples 60-65 were obtained on 28 April 1952 at position 5. It can be seen from Fig. 1 that this position would be well up within the clouds. The cloud base was at 2000 feet and the elevation at position 5 was 5500 feet. All but one of these samples are of intensities < 0.2 mm hr^{-1}. With the exception of one sample the drops are all <0.4 mm with a majority <0.2 mm. This large number of small drops can give rise to an error in the calculated intensity. This probably explains the anomalous distribution of the data.

On 5 May 1952 samples 66-73 were obtained at position 5 well within the cloud. The wind was upslope at 0.6 m sec^{-1}. The temperature was 10.8 C with a wet bulb of 10.7 C. The liquid water content for sample 70 was abnormally high. A glance at Table 1 shows that all drops in sample 70 were < 0.2 mm and in concentrations of 149,000 m^{-3}. This is the highest concentration of drops < 0.2 mm found in the present study.

On 29 April 1952 position 5 was at or near cloud top. At 1640 the cloud cover was broken with a fine mist being blown from the dense cloud cover to windward. The temperature was 14.4 C with a wet bulb of 13 C. At 1725 the wind was steady at 1.3 m sec^{-1}. By 1740 the clouds moved in over the area with a light drizzle which lasted throughout the time of sampling. From 1742 to 1909 samples 74-78 were collected. Although the intensity, as measured by the filter papers, reaches a maximum of only 2.5 mm hr^{-1}, a rain funnel measurement, obtained shortly after the last sample was taken, indicated an intensity of 4.8 mm hr^{-1}.

Simultaneous with the drop size distribution measurements at position 5, rain intensity measurements were being made at position 4. Twenty-six measurements from 1605 to 1905 indicated intensities ranging from 0.5 to 13.3 mm hr^{-1}. During the entire time the cloud base was approximately at the elevation of position 4. At 1708 the dry and wet bulb temperatures were 16.8 C and 16.7 C and at 1818 both were 15.8 C.

(b) Raindrop distributions in a dissipating orographic cloud

In some respects the drop size distributions obtained on 21 March 1952 are the most interesting. For they are measurements not only made in a dissipating cloud system but they were made at many points within the cloud system ranging from cloud base to cloud top.

It will be well to briefly discuss the topographical and meteorological features of the area in which this cloud forms. Examination of Fig. 1 immediately shows that the region of position 7 has little possibility of being influenced by the trade wind flow as is the region around positions 1-5. Leopold (1949) has shown that the 14,000 foot low angle cones formed by Mauna Kea and Mauna Loa are sufficient to split the trade wind flow into two components. Apparently the inversion is sufficient to prevent the flow from rising over mountains extending up through the inversion. Leopold has studied, in some detail, the formation of clouds in the lee of the 10,000 foot cone of Haleakala on the island of Maui, T. H. He found that a sea breeze was the dominant factor in the formation of the afternoon orographic clouds. In the late afternoon this sea breeze gives way to a downslope land breeze. In many respects, we may expect a somewhat similar mechanism of cloud formation in the lee of Mauna Kea.

At 1645 on 21 March 1952 the writer was at cloud base at position 7 at an elevation of 3100 feet. The wind was nearly dead calm and a light rain was falling. Sample 79 was taken at this point. Samples 80-83 were taken at approximately 2 mile intervals up through the cloud. Fig. 7 indicates these positions and shows the gradual uniform rise of the slope and a schematic representation of the cloud top positions at various times. Note the vertical structure of the cloud edge. Its 1000 foot height is a visual estimate.

Samples 85-87 were taken on the first downward traverse. During this time the cloud top was receding slowly and the drop distribution was shifting toward the small end. This trend in the drop distribution continued during the second upward traverse as the remaining samples, 88 and 89, were taken. From sample 86 on, a decrease was found in the number of drops in the 0.3 mm size interval and, concurrently, a steady increase in the drop count in the 0.1 mm size interval. In fact, the increase of the number of drops <0.2 mm is exponential. The equation $N = 4000\ e^{0.0715t}$ can be used to express the number at t minutes after the time of sample 86, 1803. Within 15 minutes after sample 89 the cloud was void of drops of sufficient size to register on the filter paper. The apparent "drying out" of this cloud was by no means confined to these data. On other occasions the writer has been in this cloud in the early evening and has experienced the decrease in size and eventual disappearance of raindrops.

The liquid water-intensity relationship (Fig. 8) shows a fairly uniform trend with the exception of the last two samples. The large increase in W associated with these is what would be expected. Note that for the same liquid water content of sample 89, a 17 fold increase in intensity would be required to fit Best's (1950) results.

The existence of trade wind eddies in the lee of Mauna Kea and high level air flowing from east to west through the Mauna Kea-Mauna Loa saddle (Leopold, 1949) makes it very difficult to

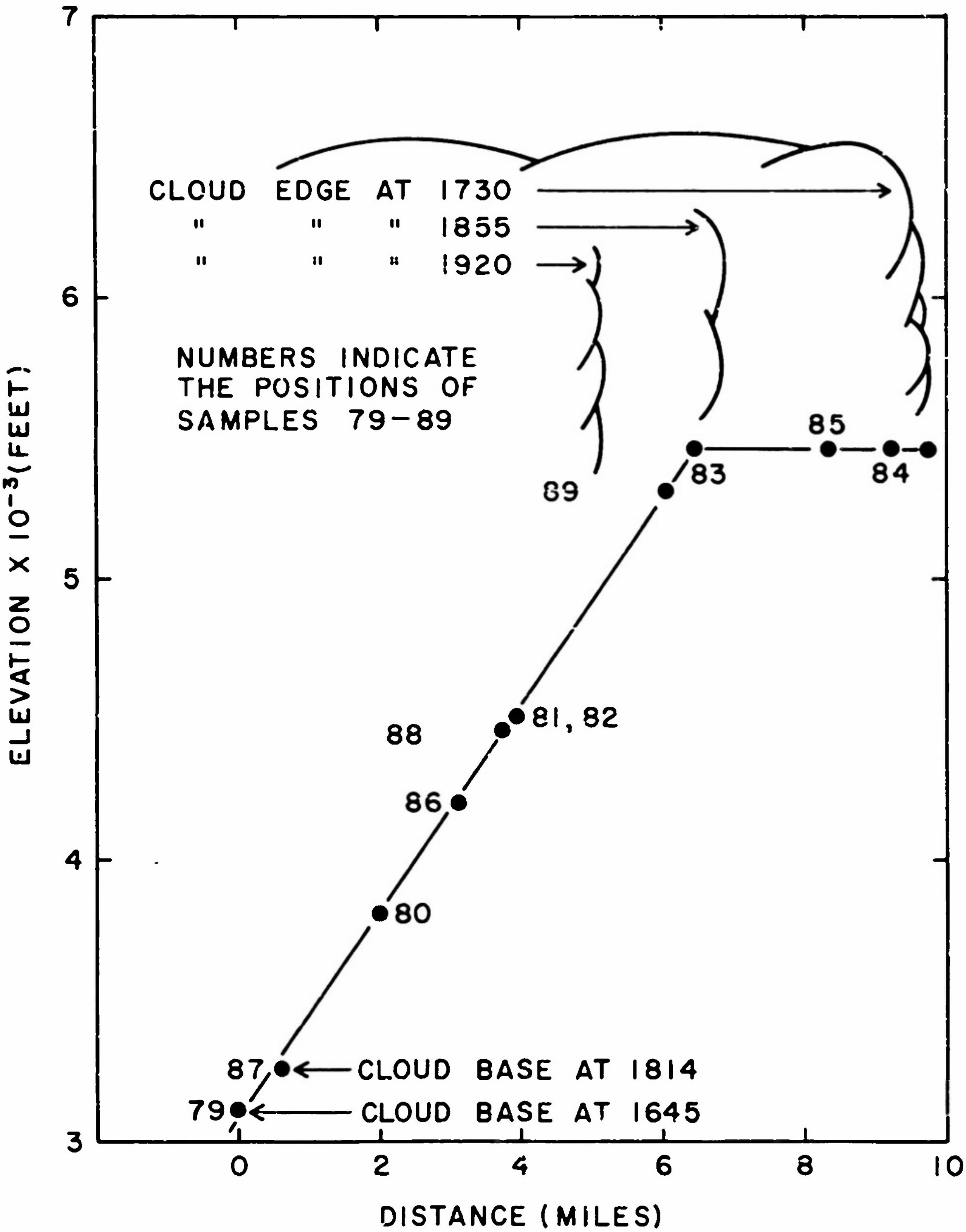

Fig. 7 The uniform slow rise of the terrain (370 feet mile^{-1}) at the area where samples 79-89 were obtained. The numbers alongside the points indicate the position of the samples. Although the abscissa indicates the horizontal distance between points it is to be taken as the distance measured along the slope. (Actually the difference is negligicle).

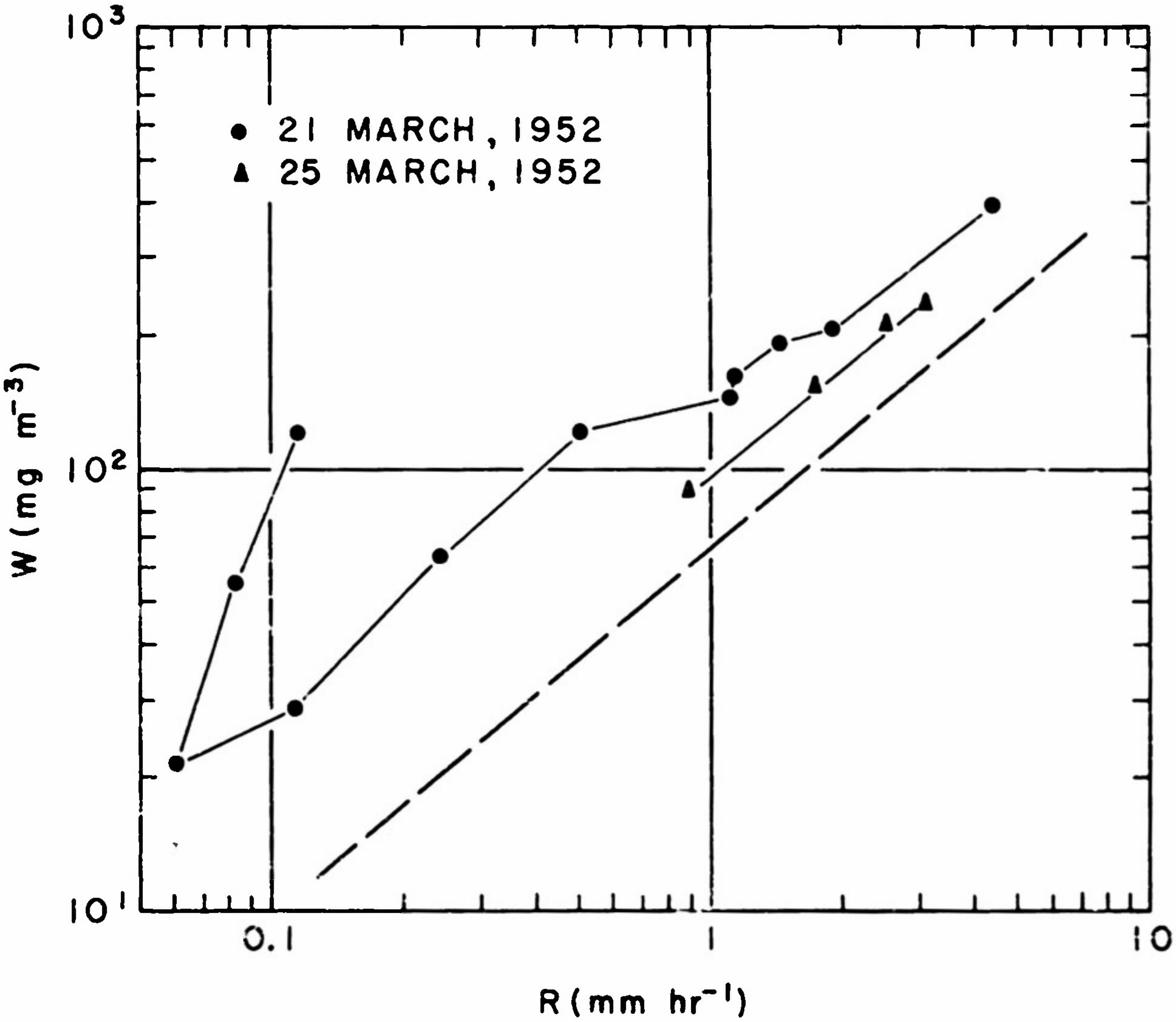

Fig. 9 W vs. R relationship for samples 79-93. The dashed line is the locus obtained by Best (1950). The lines connecting the points are visual aids only.

ascertain the past history of the air in this area. Woodcock's measurements have shown that significant differences in the distributions of air-borne salt particles are a function of not only wind velocities but, in some cases, of the topographical features over which the air flows. On 21 March 1952 the estimated winds to windward of the island were Beaufort force 4-5. At such speeds the concentrations of air-borne salt particles at cloud base would be of the order of 6000-10,000 particles m^{-3} between 10^2 and 10^4 $\mu\mu g$. The equilibrium diameters of salt particles of 10^2 and 10^4 $\mu\mu g$ at an R.H. of 99 per cent are 22 and 102 microns, respectively. And yet, on this particular day, measurements obtained from aircraft just below cloud base to leeward from Mauna Kea failed to show the existence of any salt particles $>10^2$ $\mu\mu g$. Ordinarily this would be typical of air only above the inversion. Whether the explanation is that this air is high level air which has flowed down the mountain during the night, or whether it represents salt depleted air which has passed through the saddle area from clouds on the windward side of the island, the writer cannot say. It is apparent, however, that the presence or absence of these large salt particles should profoundly effect the rain producing characteristics of the clouds.

It may well be that the rain of 21 March 1952 came from a cloud which had formed in air of low salt particle and condensation nuclei concentration. It is suggested that supersaturation may occur and the growth of the sparse population of cloud droplets may be by condensation processes only.

Three days later, on 25 March 1952, samples 90-93 were taken at the 5500 foot level. In Fig. 8 and Table 1, the difference in the characteristics of the "lee-side" distribution is obvious. A scarcity of droplets exists in the first two size intervals. As no aircraft salt measurements were made on this day it is impossible to tell if the salt particle distribution resembled that of 21 March.

(c) Drop distributions at cloud top and base

On 1 May 1952 a series of 10 drop distribution measurements, samples 94-103, were obtained at cloud base, an intermediate point, and near the cloud top. These are positions 1, 2, and 3 on Fig. 1 with elevations of 2200, 3400, and 4000 feet, respectively. Samples 94-96, obtained at position 1, contain some of the largest drops found in orographic rain. Samples 97-100 were obtained at position 2, 6.6 miles upslope from position 1. The remaining samples were obtained at position 3, 8.8 miles upslope from position 1. At position 3, near cloud top, a great increase in numbers of drops between 0.2 and 0.6 mm was found. Fig. 9 shows the difference in drop distribution at the three positions expressed in terms of the liquid water content.

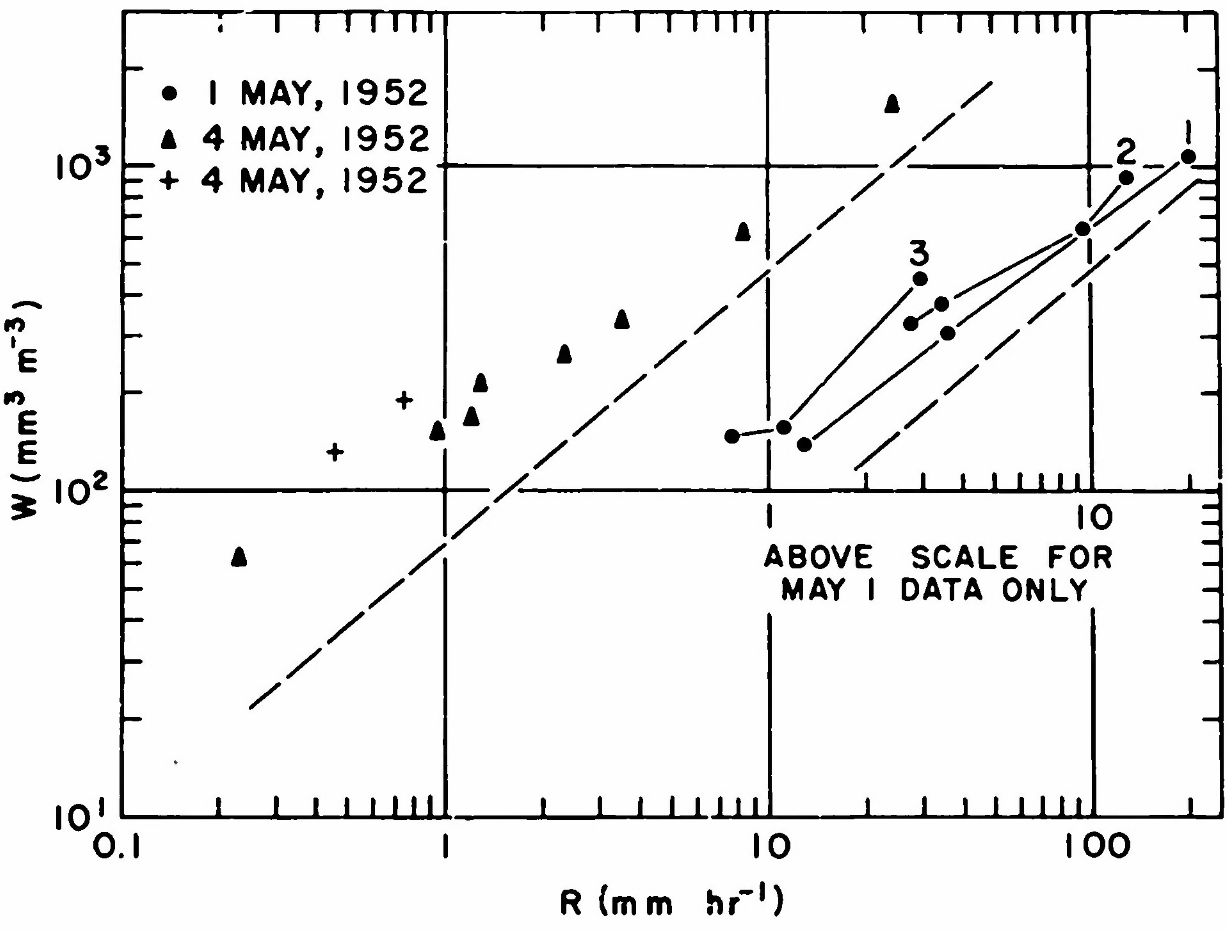

Fig. 9 W vs. R relationship for samples 94-113. The numbers alongside the May 1 data indicate the sampling position. The May 4 data, indicated by the crosses, were obtained at position 3. The dashed line is the locus obtained by Best (1950).

On 4 May 1952, samples 104-113 were obtained at positions 1 and 3. At 1730 at position 3 both wet and dry bulb readings were 13.4 C. A difference in drop distribution between the two positions is illustrated in Fig. 9. This difference becomes numerically clear by inspection of Table 1. The large numbers of drops $<$ 0.4 mm is sufficient to cause a high liquid water content.

8. The median volume diameter as a function of rain intensity

Many of the data of Table 1 have been expressed in Fig. 10 in terms of median volume diameter. The median volume diameter is that diameter which divides the drop distribution into two parts such that each represents half of the liquid water content W. It is obtained by plotting a cumulative per cent curve of the liquid water content. The percentage corresponding to any drop diameter is the percentage of the total liquid water content contained in the drops $<$ the drop in question. The drop diameter at the 50 per cent ordinate is, therefore, the median drop diameter.

In addition to the data from the Hawaiian orographic rains, data from non-orographic rains (samples 1-30 and drop distributions obtained at Woods Hole, Massachusetts) have been included. The median diameters of the non-orographic samples alone show considerable spread at all intensities. Considering the differences in the synoptic situation represented by each of the rains this spread is to be expected. With the exception of four of the samples from the Mauna Kea and Woods Hole data, all the median diameters greatly exceed those found in orographic rains of the same intensity. Note that the three Mauna Kea samples (1, 10, 11, Table 1) which fall into the orographic grouping have drop distributions representative of orographic rains.

The solid line was drawn from the data of Laws and Parsons (1943) and the dashed line from the data of Anderson (1948). Laws and Parsons used the flour technique for drop size sampling (Bentley, 1904) and calculated the intensity of rainfall from the exposures, area, and drop distribution of the sample. All of their rain samples were obtained at ground level at Washington, D. C.

Anderson's results are extremely interesting in that they were taken on the island of Hawaii in the vicinity of position 4 (Fig. 1). Some 60 samples were obtained with the blotting paper method over a period of 5 hours. The disagreement of Anderson's data with the present data and the relatively good fit with that of Laws and Parsons suggests that his sampling was in a particular rain not representative of the general Hawaiian rains. Of the 60 samples, only 3 were taken at intensities $<$8 mm hr^{-1}

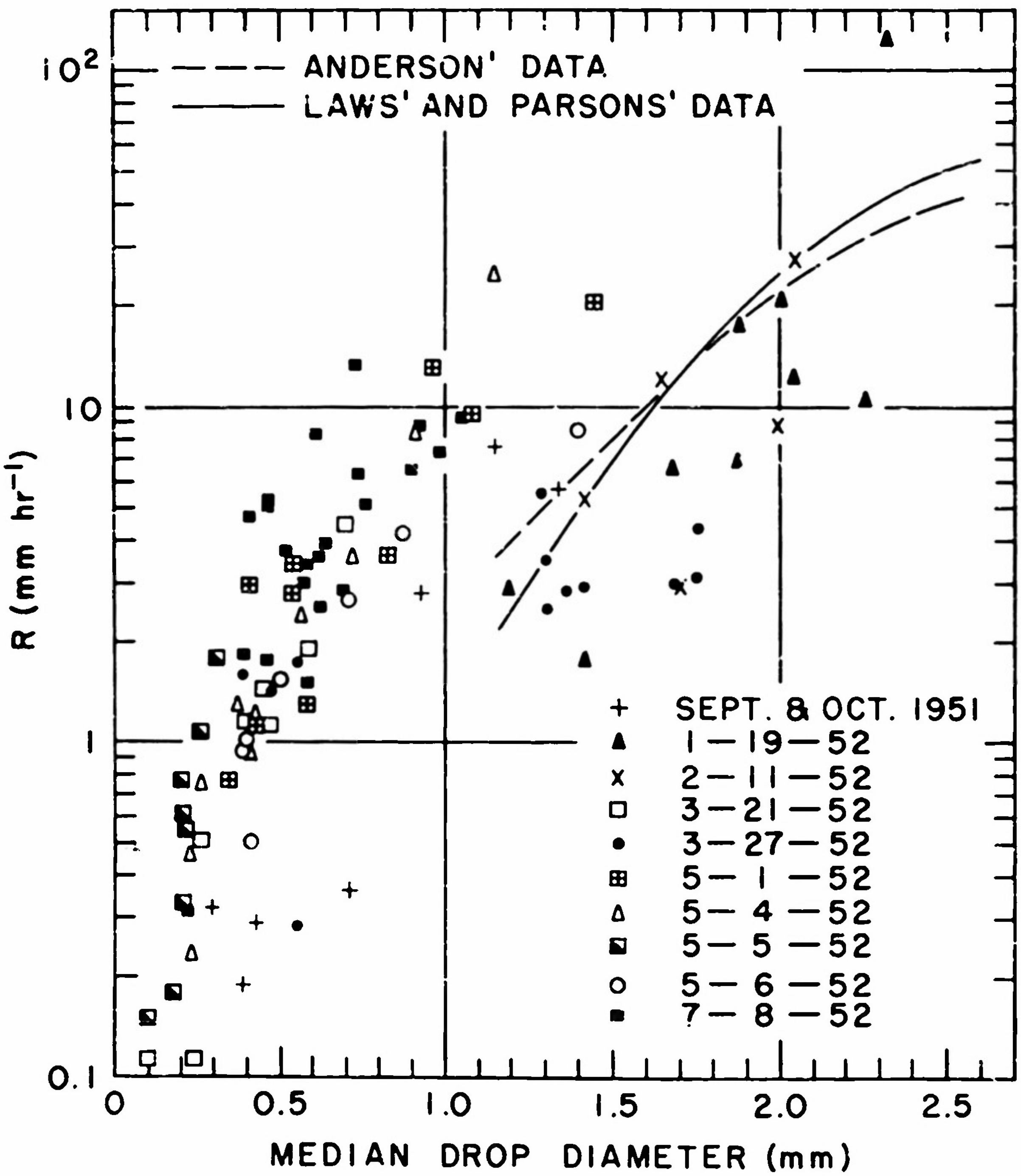

Fig. 10 The median volume diameter as related to the rain intensity. The data labeled Sept. - Oct. 1951 were obtained at Woods Hole, Mass. The median volume diameters, as found in the orographic rains, are considerably less than those found in non-orographic rains.

and none at intensities < 2.5 mm hr^{-1}. Anderson states* that the rain appeared to be orographic in nature and was accompanied by light winds. It is possible, however, that this rain was similar in origin to that of samples 1-13, evolving from snow from high level supercooled clouds. From a meteorological point of view this was quite possible. Anderson's work was carried out on 16 March 1945, the same time of the year as samples 1-13. During the winter months and extending through March it is not an infrequent occurrence to have rain of this nature.

The quartile deviation for orographic rain, a measure of the spread of the liquid water content, is considerably lower than that reported by Anderson. The present data indicates values ranging from 0.01 to 0.15 as compared to Anderson's measurements of 0.1 to 0.8. The writer finds, as did Anderson, that the quartile deviation is roughly proportional to the median diameter. This, of course, implies a decreasing slope of the cumulative per cent curve between the first and third quartiles with increasing median diameter. According to Anderson this is contrary to the cumulative per cent curves of Laws and Parsons which show a nearly constant slope between the first and third quartiles at all median diameters.

9. Radar reflectivity

The success of radar in determining the intensity of precipitation is dependent on a knowledge of the size distribution of the precipitation elements. The power received at a radar from a rain target is proportional to the radar reflectivity $Z = ND^6 \delta D$ where N is the number of drops m^{-3} of diameter D in the size interval δ D. It is apparent that the sixth power of the diameter factor allows the relatively few large drops to greatly influence the radar reflectivity.

Wexler (1948) and Marshall and Palmer (1948) have computed, from their own data and that of other investigators, the relationship between Z and rain intensity R. Recently, similar relationships have been found to hold for various spectrums of cloud droplets (Atlas and Boucher, 1952). Marshall and Gunn (1952) report that the Z versus R relation has been found to be interchangeable for rain and snow. That is, for equal rates of precipitation, whether rain or snow, they obtain the same values of Z. Higgs (1952) has presented the results of Z calculations made in Australia. He points out that, for a given intensity, the drop size distribution may vary considerably. This, of course implies a corresponding variation in Z. Higgs has

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* Private communication.

presented a list of Z-R equations obtained by many investigators at widely separated localities. Considerable disagreement exists in these equations. They range from $Z = 23.5R^{2.028}$ to $Z = 1600R^{1.4}$. The Australian results alone indicate that the rain intensity, as deduced by radar, may be in error by a factor as great as 4 to 1.

These variations in the Z-R equations are not surprising. They undoubtedly represent rains whose origins lie in snow producing clouds, non-freezing cumuliform clouds, and orographic type clouds. Further variations are probably introduced by the evaporation and collision of drops in the sub-cloud region (see section 4). Fig. 11 shows how the Hawaii data alone varies in Z for a given R. The Z-R relationship for samples 1-30, the non-orographic rains, most nearly corresponds with that of other workers. The regression line shown was not drawn on the basis of these data. It represents the least squares regression of 63 rain samples, both from continuous and shower-type rain, taken at Cambridge, Massachusetts (Mt. Washington Observatory, 1951). A least squares fit has not been determined for the 3 types of rain represented by samples 1-30 but, excluding samples 1 and 10, it would probably agree closely with the Mt. Washington curve. Samples 1 and 10, as seen by Table 1 and discussed in section 5a, are representative of orographic rain and would, therefore, show relatively low values of Z.

The Hawaiian orographic rains of low intensity (< 2 mm hr^{-1}), as compared with the non-orographic rains, may give lower values of Z by as much as a factor of 30*. At intensities > 10 mm hr^{-1} a factor of from 4-10 is found. Inasmuch as day by day variations exist it is not felt necessary to present any least square fits. However, it can be easily seen from inspection of Fig. 11 that the coefficient in the Z-R equation will be from 10 to 100, considerably lower than those found elsewhere. The data of 1 May 1952, obtained at 3 different positions within the cloud, illustrates the small but noticeable difference in Z in various parts of the cloud.

If the type of rain, i.e., thunderstorm, frontal, orographic, is not known a large error may be made in determining R by radar. In agreement with the Australian findings the error may be as large as a factor of 4.

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* A factor of 15 is probably the usual case. The factor of 30 was based on the 5 May 1952 data, obtained near the cloud top. Only in the case of a subsiding cloud (samples 79-89) would one expect to find such a drop distribution at cloud base.

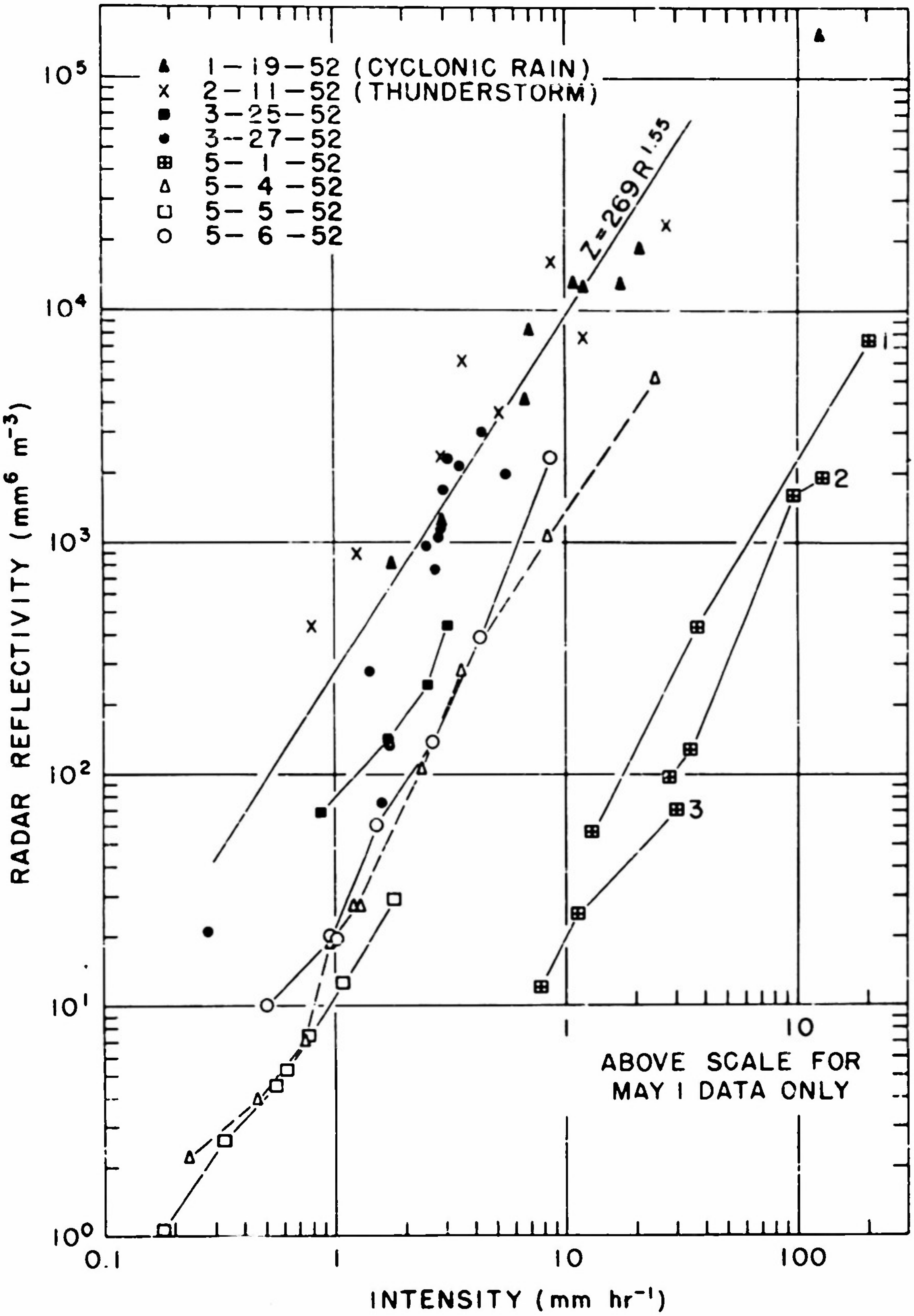

Fig. 11 Radar reflectivity as a function of rain intensity. The locus $Z=269R^{1.55}$ is not that of the present data but one obtained by the Staff of the Mt. Washington Observatory in a least squares analysis of the Z vs. R relation of continuous and shower-type rain at Cambridge, Mass. The numbers connected with the May 1 data represent the sampling positions. The lines connecting the points are visual aids only.

10. Summary and conclusion

1. A given drop size distribution can be modified by wind shear, relative fall amongst the drops, evaporation, and drop coalescence, in the fall from cloud to ground. Although some of these factors are at work within the cloud itself it is certain that drop size sampling at the cloud base will minimize the errors contributed by these factors. The evaporation will be most important, especially in the case of the semi-tropical orographic rains discussed in the present study. In these rains the many thousands of drops $m^{-3} < 0.5$ mm that are normally present may evaporate completely in a sub-cloud fall of 1000 meters. This evaporation was eliminated in the present work by obtaining the orographic drop distributions on the sides of the volcanoes of the island of Hawaii at cloud base or within the cloud itself.

2. Drop distributions have been obtained in rain beginning as snow in freezing clouds. The differences in drop distribution, liquid water content, median volume diameter, and radar reflectivity from that of orographic rains is apparent from Table 1 and Fig. 4-11.

   The liquid water content W has been used as a measure of the drop distribution. A wide distribution with relatively few drops, both large and small, will give a lower value of W, for the same intensity, as will a narrow distribution composed of many small drops. W-R relationships for non-orographic rains have been found to agree reasonably well with that of Best (1950).

3. The distribution of raindrops in semi-tropical orographic clouds is decidedly different from those presented in the literature. The maximum drop size seldom exceeds 2 mm and concentrations of drops < 0.5 mm often exceeds 25,000 m^{-3}. It seems probable that these drops evolve first by condensation on large air-borne salt particles and then by accretional processes with the numerous cloud droplets.

   The raindrop distribution near the top of orographic clouds is concentrated at the small end of the spectrum. The appearance of drops > 0.6 mm is exceptional.

4. The median volume diameter, the drop diameter at which the total volume of water m^{-3} is divided equally, has been used as a measure of the intensity of rainfall. For a given intensity in an orographic rain the median volume diameter is about half that found in thunderstorm and frontal type rains.

5. The radar reflectivity Z in an orographic rain is a factor of 10-20 less than that found in thunderstorm type rains. Variations in Z have been found in orographic rain from day to day.

11. Acknowledgments

The writer would like to thank Mr. Alfred H. Woodcock for his assistance in obtaining many of the data used in this study. He is grateful to Mr. Wendell A. Mordy of the Pineapple Research Institute and Hawaiian Sugar Planters Association for the opportunity to carry out the experiments.

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Table 1

No.	Date	Time (Hawaiian Standard)	Position	Intensity	Number of Drops m^{-3} 0.2 mm^{-1} Size Interval 0.1	0.3	0.5	0.7	0.9	1.1	1.3
1	3-27-52	0814	6	1.6	11,200	5,800	590	172	80		
2	"	0842	"	3.5	*	250	100	44	24.5	43	15
3	"	0845	"	3.1	*	182	25	31	25	14	6.1
4	"	0858	"	2.95	*	248	92	49	25	16	8
5	"	0908	"	4.4	*	315	125	42	32	22	9.7
6	"	0914	"	5.5	*	630	260	158	109	60	35
7	"	1118	"	2.9	*	191	110	35	32.5	37.5	20.8
8	"	1120	"	2.8	*	430	23.5	36	53	41	17
9	"	?	"	2.7	*	420	162	45	82	43	30.5
10	"	1412	"	1.7	5,700	1,500	900	162	61	36.5	
11	"	1420	"	1.4	8,100	2,600	430	59	26	16.8	9.6
12	"	1640	"	2.5	*	520	252	72	47	18.3	3.2
13	"	2025	"	0.28	521	471	100	28.5	10.2	5.75	
14	1-19-52	1031	8	2.9	9,300	700	120	50	56	50	22
15	"	1056	"	1.8	2,200	160	39	9.2	17	15.5	16
16	"	1108	"	7.0	14,000	560	130	49	7.6	46	5.8
17	"	1135	"	10.7	11,000	1,050	82	34	55	19	--
18	"	1150	"	127	*	*	1,650	320	165	185	124
19	"	1514	"	6.7	1,240	230	94	31	37	52	46
20	"	1516	"	12.1	1,600	225	41	48	11	23	12
21	"	1525	"	20.8	460	190	94	77	54	70	15
22	"	1533	"	17.5	1,500	700	150	39	68	31	50
23	2-11-52	1354	"	0.8	--	--	--	--	1.5	0.7	0.5
24	"	1355	"	3.6	--	--	2.8	--	1.8	1.5	1.4
25	"	1356	"	1.25	--	--	2.1	10.5	4.1	2.3	1.0
26	"	1401	"	8.8	2,900	360	120	54	24	10	14
27	"	1402	"	27.5	11,200	680	230	55	120	66	65
28	"	1404	"	12.0	2,400	480	86	13	25	21	52
29	"	1409	"	5.25	3,600	690	210	95	105	26	26
30	"	1419	"	2.9	3,500	140	13.5	5.6	29	--	1.6
31	7-8-52	1423	1	1.5	--	440	970	300	43		
32	"	1433	"	3.4	830	2,240	1,880	530	139	13	

Table 1 (Cont'd.)

Number of Drops m^{-3} 0.2 mm^{-1} Size Interval

No.	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9
1													
2	13	9.2	5.7	--	2.6	--	2.35						
3	7.3	6.7	1.6	7.4	2.85	1.37	1.3						
4	7.4	11.8	7.8	3	1.4	1.4							
5	22	2	11.3	3.55	5	1.62	1.52						
6	41	4.8	8.3	--	4								
7	15.5	8.6	7.9	--	1.2								
8	20	4.7	5.8	2.7									
9	13	3	5.5										
10													
11	--	--	3.6										
12	14.5	7.9	2.5	4.7									
13													
14	15	8	--	--	1.7	1.6							
15	8.6	5.7	2.1	--	0.94	0.9							
16	15.5	14.5	8.8	4.2	--	3.8	3.7	--	--	3.4			
17	29	13.5	--	6.8	11.5	2.7	10	--	2.45	2.4			
18	135	34	73	170	230	63	61	32	8.2	24			
19	12	3.7	21	10	6.2	3							
20	44	20	22	12	11	2.7	7.7	--	--	--	2.3		
21	36	38	59	15	28	6.7	3.2	--	--	--	3.1		
22	70	42	24	17	22	9	--	--	2.9				
23	3.1	1.4	4	1.3	0.4								
24	--	1.15	1.02	1	2.8	2.7	4.4	1.5	1.44	0.7			
25	2.8	2.5	3.2	3	1.4	0.7							
26	32	22	17	3.3	3.1	6	8.6	--	--	--	--	--	2.5
27	44	34	50	36	17	27	10	5					
28	70	50	32	5.4	2.6	4.8	4.6						
29	20	15.5	8.5	--	2.6	--	--	--	2.2				
30	19	4.1	5	3.6	1.15	1.1	1.04	1					

Table 1 (Cont'd.)

Number of Drops m^{-3} 0.2 mm^{-1} Size Interval

No.	1.5	1.7	1.9	2.1
33	10.3	28.8	8.8	
36	20.4			
37	6.6			
38	7.3			
58	125	13.5		
82	5.6			
92	4			
96	202	22.5	55.2	6.6
97	21.8			
112	85	11.2		

Table 1 (Cont'd.)

No.	Date	Time (Hawaiian Standard)	Position	Intensity	Number of Drops m^{-3} 0.2 mm^{-1} Size Interval 0.1	0.3	0.5	0.7	0.9	1.1	1.3
33	7-8-52	1437	1	9.2	--	1,640	356	510	310	160	93
34	"	1442	"	3.9	--	850	2,000	660	208	9.3	
35	"	1445	"	6.2	730	2,000	2,050	720	153	180	31
36	"	1451	"	7.3	--	1,010	472	236	464	240	35
37	"	1509	"	2.6	--	592	1,320	282	79	17	15
38	"	1517	"	6.5	--	340	920	660	208	235	32
39	"	1526	"	2.8	--	1,150	1,280	535	175	56	8.1
40	"	1539	"	3.8	--	1,740	3,100	450	92	13.2	
41	"	1545	"	1.8	122	2,100	1,670	180	17.7		
42	"	1605	"	5.1	--	870	1,460	620	375	71	10
43	"	1617	"	8.7	--	740	1,240	680	490	320	31
44	"	1629	"	5.3	245	7,400	6,000	300	18.2		
45	"	1655	"	0.31	20,000	2,700	28	23			
46	"	1714	"	5.05	75,000	6,600	4,200	460	146		
47	"	2142	4	13.3	45,000	10,900	2,200	1,700	540	332	55
48	"	2146	"	3	1,600	3,400	1,650	520	98		
49	"	2150	"	3.6	4,700	4,600	810	635	177	23	6.7
50	"	2155	"	4.7	29,200	13,700	4,000	248	98		
51	"	2203	"	1.8	9,000	9,400	1,030	152	10.8		
52	"	2208	"	8.2	4,600	2,480	4,400	1,400	280	83	
53	5-6-52	1648	"	1.02	2,270	4,200	1,058				
54	"	1654	"	1.5	3,870	3,210	890	287	19.8		
55	"	1710	"	0.95	4,800	4,050	790	41			
56	"	1718	"	0.51	2,000	1,600	580				
57	"	1721	"	2.6	2,000	2,170	524	590	168		
58	"	1732	"	8.5	*	790	280	82	87	121	65
59	"	1735	"	4.2	1,580	1,080	137	355	550	31	
60	4-28-52	1656	5	0.056	48,700	85					
61	"	1724	"	1.82	116,000	11,500	1,150				
62	"	1735	"	0.21	41,500	2,040					
63	"	1807	"	0.046	25,400	243					
64	"	1820	"	0.15	78,500	930					
65	"	1835	"	0.11	110,000						

Table 1 (Cont'd.)

No.	Date	Time (Hawaiian Standard)	Position	Intensity	Number of Drops m^{-3} 0.2 mm^{-1} Size Interval 0.1	0.3	0.5	0.7	0.9	1.1	1.3
66	5-5-52	2038	5	0.77	101,000	7,030	144				
67	"	2051	"	1.8	65,000	11,200	1,120	27			
68	"	2117	"	0.62	80,800	6,400	33				
69	"	2132	"	0.18	66,200	1,360					
70	"	2150	"	0.15	149,000						
71	"	2216	"	0.33	29,500	3,600					
72	"	2230	"	0.55	51,000	6,100					
73	"	2255	"	1.08	19,400	11,000	280				
74	4-29-52	1742	"	1.15	4,300	6,100	900	11.2			
75	"	1800	"	2.5	2,450	5,400	2,060	270	24.2		
76	"	1813	"	2.1	16,000	13,000	1,540	19.6			
77	"	1847	"	0.17	71,300	1,170					
78	"	1909	"	0.66	10,500	6,100	480				
79	3-21-52	1645	7	1.12	2,380	2,050	900	110	27		
80	"	1655	"	0.11	2,550	1,350	4.4				
81	"	1702	"	1.9	820	1,150	1,160	400	41		
82	"	1705	"	4.44	1,470	1,780	1,290	601	159	63.6	25
83	"	1718	"	0.24	8,800	2,800	12				
84	"	1727	"	1.44	7,800	2,800	1,640	34			
85	"	1745	"	1.14	4,600	3,950	580	94	47		
86	"	1803	"	0.51	4,600	6,200					
87	"	1814	"	0.061	8,310	666					
88	"	1837	"	0.083	43,000	495					
89	"	1850	"	0.12	114,000						
90	3-25-52	1812	7	0.9	730	470	490	134	8.2	14.3	3.1
91	"	1813	"	2.54	640	129	600	240	195	58	
92	"	1815	"	3.1	490	400	215	390	92	94	27
93	"	1825	"	1.74	640	420	400	215	170	11.3	
94	5-1-52	1326	1	1.3	600	360	920	270	18		
95	"	1341	1	3.6	2,000	1,500	385	390	265	52	26
96	"	1344	1	20.5	1,308	1,282	369	76	206	164	198

Table 1 (Cont'd.)

No.	Date	Time (Hawaiian Standard)	Position	Intensity	Number of Drops m^{-3} 0.2 mm^{-1} Size Interval 0.1	0.3	0.5	0.7	0.9	1.1	1.3
97	5-1-52	1555	2	13	1,300	305	248	800	950	405	65
98	"	1608	"	3.4	534	804	3,470	436	39.6		
99	"	1625	"	9.6	1,100	385	169	245	305	540	83
100	"	1638	"	2.8	1,010	2,950	2,350	440	10.8		
101	" "	1500	3	3	--	8,300	3,860	30.5			
102	"	1505	"	1.1	270	2,820	1,350	12.5			
103	"	1513	"	0.77	800	5,800	485				
104	5-4-52	1707	3	0.75	20,000	8,600	56				
105	"	1735	"	0.46	28,500	5,400					
106	"	1810	1	0.95	1,358	4,320	855	21.1			
107	"	1815	"	1.2	2,000	3,200	1,300	43			
108	"	1820	"	1.3	4,750	6,900	971	21.1	8.4		
109	"	1827	"	0.23	11,400	2,610	18.8				
110	"	1833	"	3.6	620	1,700	850	620	225	39.5	
111	" "	1844	"	2.4	370	1,800	1,770	390	40.5	5.8	
112	"	1846	"	24.8	--	290	196	251	710	850	410
113	"	1850	"	8.5	--	111	520	690	670	194	54