The Origin of Trade-Wind Orographic Shower Rains

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Abstract

The purpose of the work reported here was to learn more about rain formation through a study of the extensive Project Shower and other data on the physics and the chemistry of rains. Most of the observations used have been published. It is demonstrated that the water and chloride content of orographic shower rains in Hawaii can be roughly computed from the observed amounts of sea-salt aerosols and water vapor in the sub-cloud layer over the sea, assuming wet adiabatic ascent of the air. From this and several other relationships among the properties of the air and rains, it is tentatively concluded that the showers originate within especially moist parcels of air which are carried into the orographic cloud by the trade winds, and which were previously formed in the sub-cloud layer over the windward sea. Specific suggestions are made for testing the degree to which potential shower-forming air may be identified over the sea or the windward shore prior to rain formation.

1. Introduction

Since the beginning of the century numerous workers have, for various reasons, been interested in the chemistry of precipitation (see review papers by ERIKSSON 1952 and JUNGE 1958). Among the many results of this world-wide interest has been the discovery that the chloride concentration in rains tends to decrease with increases in rain amount. In the present paper, the numerous data concerning the chlorinity and other properties of the rain and the atmosphere are examined in order to see what deductions can be made, if any, about rain-forming processes. Recently derived information about the individual sea-salt particles in the atmosphere is also utilized.

The presence of chlorides in precipitation waters has long been used as an example of the capacity of rain to "wash" particulate and other matter from the air as the drops fall from cloud base to ground. Recent tests in 1951 and 1952 (WOODCOCK and BLANCHARD 1955) revealed, however, that similar chloride concentrations were also present in rains sampled within the rain-producing clouds, making it necessary to revise the "washout" idea of earlier workers to include washout from the cloudy air as well as sub-cloud air. In the present paper it is demonstrated that, through alterations in the time, duration and position of rainwater sampling, one can reveal useful relationships between the chloride concentrations and other characteristics of the rains and of the atmosphere from which they fall.

The Project Shower data resulting from a cooperative field study of Hawaiian trade-wind orographic showers (SQUIRES 1955), is the primary source of the information used in the present work. These data have been given in a series of reports in Tellus vol. 9, No. 4, 1957.[1]

2. Comparison of observed and computed chloride concentrations in rains

In a previous study of the rains of Hawaii (WOODCOCK and BLANCHARD 1955) is was computed from observational data and with certain assumptions, that about 20 to 40 per cent of the airborne salt could be found in solution in the rains which fall near cloud-base altitude

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[1] Hereafter referred to by the abbreviation PST.

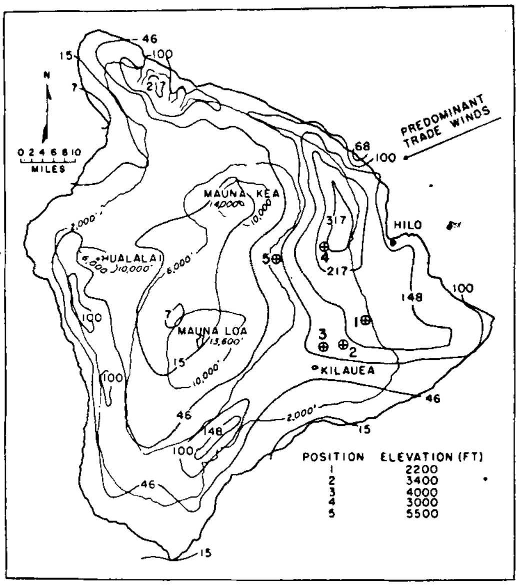

Fig. 1. Isohyetal map of the island of Hawaii, showing the locations of the earlier rainsampling stations. The later more elaborate study required the expanded network shown in Fig. 2.

(stations 1 and 4, Figure 1). These rain showers drift in the wind stream up the mountain slope, the rain being "winnowed" in the general direction of stations 3 and 5 as indicated by BLANCHARD (1957). Rain samples taken at position 5 were found to contain only about five per cent of the salt. It was suggested at the time that the remainder of the salt and water of the rains might be found among the drops which fall over the intervening distance of about 20 km.

During the Project Shower field program, daily rain amounts were sampled at closely spaced stations roughly along the average line of drift of the trade-wind air, with the purpose of examining this idea of winnowed drops. From these samples numerous data are available showing the daily rainfall and saltfall as a function of distance downwind and up the mountain slope from stations 32 and 5 on the Kulani and Saddle Roads (see Figure 2). In this section the properties of the rains from these locations will be shown to be related to the amounts of airborne salt particles and the amounts of water condensed in the clouds.

The purpose here is to present an analysis of a part of the published Project Shower data which indicates that the Hawaii orographic shower rains are produced in certain parcels of air. In simple terms, the actual operation performed here is a comparison of the ratios

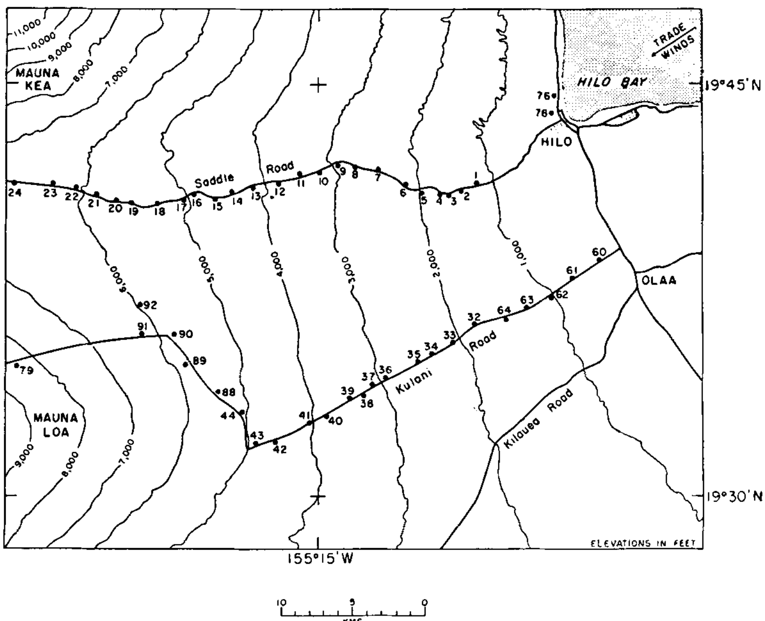

Fig. 2. Map of a section of the windward side of the island of Hawaii. The numbered dots on the Saddle and Kulani roads mark the positions of the Project Shower rain gages used in the present study.

Table 1. Data used in comparing the average chlorinity of the orographic shower rains of Hawaii to the chlorinities derived by the use of the "shower parcel" model

			a	b*	c*	d	e	f	g	h
Date	Rain Sampling		Airborne Chloride particles	Rainfall	Saltfall (in rain)	Cloud base altitude over sea	Cloud top altitude	Water content of rain	Chloride conc. of rain observed (c/b)	Chloride conc. of rain comp. (a/f)
	position	duration hours	µgms kg^{-1}	10^6 liter	10^6 mg Cl	m	m	gms kg^{-1}	mg l^{-1}	mg l^{-1}
Oct. 1954										
19—20	S	24	3.1	0.34	0.36	336	2,410	3.8	1.0	0.7
20—21	S	»	9.2	1.08	3.96	610	2,740	4.0	3.7	2.3
25—26	S	»	6.4	0.80	0.05	»	2,920	4.2	0.1	1.5
»	K	»	»	0.49	0.20	»	»	»	0.4	»
26—27	S	»	»	0.51	0.23	»	2,470	3.5	0.5	1.5
»	K	»	»	0.67	1.02	»	»	»	1.5	»
Nov. 1954										
2—3	S	24	6.5	0.08	0.22	458	1,830	2.5	2.7	2.6
»	K	»	»	0.08	0.39	»	»	»	4.8	»
6—7	S	»	3.9	0.80	0.14	404	3,020	5.0	0.2	0.8
»	K	»	»	0.69	0.45	»	»	»	0.7	»
7	S	3	4.9	0.11	0.07	503	2,710	4.2	0.6	1.2
»	K	»	»	0.12	0.12	»	»	»	1.0	»
9—10	S	24	2.8	0.14	0.19	305	2,010	3.1	1.3	0.9
»	K	»	»	0.16	0.23	»	»	»	1.5	»
25—26	S	»	6.8	0.27	0.37	915	3,110	3.6	1.4	1.9
29—30	S	»	8.5	0.27	0.71	670	2,860	4.0	2.6	2.1
»	K	»	»	0.28	0.95	»	»	»	3.4	»
Dec. 1954										
N30—1	S	22	11.9	0.40	1.34	610	2,840	4.1	3.3	2.9
»	K	»	»	0.49	2.23	»	»	»	4.6	»
1—2	S	24	10.7	1.24	2.38	630	3,260	4.8	1.9	2.2
»	K	»	»	0.88	3.14	»	»	»	3.5	»
2	S	2	11.1	0.17	0.34	640	3,020	4.4	2.0	2.5
»	K	»	»	0.09	0.35	»	»	»	3.9	»
2—3	S	21	9.3	1.10	0.93	610	3,140	4.5	0.8	2.1
»	K	»	»	1.34	0.82	»	»	»	0.6	»
3—4	S	24	5.2	0.11	0.19	900	2,220	2.1	1.8	2.5
»	K	»	»	0.15	0.37	»	»	»	2.4	»
3	S	2.5	—	0.06	0.09	670	3,050	4.5	1.5	—
»	K	2.5	—	0.05	0.03	»	»	»	0.7	—

* Rain and salt falling on a strip one meter wide, which extends from gages 5 and 32 to the upper limits of the rain areas.

of the total saltfall and rainfall on the mountain to the ratio of salt load of the sub-cloud air and the total water condensed as this air ascends in the clouds.

The information used to derive these ratios is listed in Table 1, along with other pertinent facts which will enable the reader to find the original data in PST. The primary observations are contained in columns a through h, Table 1, and are discussed in that order below.

a. The quantities of chloride in the sub-cloud air over the sea are taken from pages 522 and 523 (PST), and are the sums of the products of the median number particle weight in each weight range category and the number of particles in each range.

b. Integrated total amounts of rainfall in rain gages 5 through 25 on the Saddle Road and numbers 32 through 44 on the Kulani Road are given. Uniform steps of about 1,570 meters were used in this integration, in order to smooth out small differences in the spacing of the sampling station. The rainfall amounts given represent the total falling on a strip one meter wide.

Effectively samples are thus obtained at various successive times in the life histories of the showers, which begin on the lower slopes and rain out as they drift up the slope about parallel with the lines of sampling stations (see Figure 2). Only stations within the orographic clouds are included in this analysis, thus avoiding any question of salt collected by the rain in falling from cloud base to ground. (Excluded from this analysis are the Kulani Road data of November 26—27, which included rains of the 25th to 26th, and the Kona Storm rains of the 27th to 29th of November, when flights were cancelled.)

c. Integrated total fall of chloride dissolved in the rains is derived in the same manner as the integrated rainfall discussed above under (b).

d. Cloud base altitudes over the sea as measured by aircraft are given. These were found on occasion to differ by one hundred meters or more in places only a few miles apart. The altitudes given are the minimum values observed during the flights.

e. The average altitude at which the radiosonde record showed drying of the air ≤ 50 % relative humidity. Four ascents were made daily (PST pp. 569 to 580). This drying of the air was often associated with the trade-wind temperature inversion, but is thought to be a better indicator of average cloud top than is the temperature.

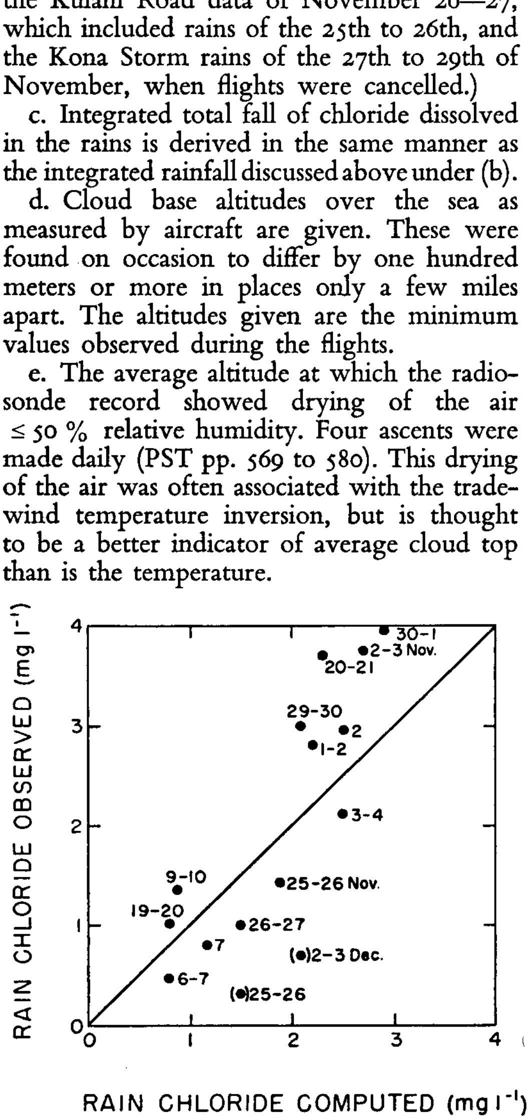

Fig. 3. A comparison of the average observed chlorinity of the integrated total rainfall on the Saddle and Kulani roads and the rainfall chlorinity computed from the "shower parcel" model. The numbers near the points refer to the days of the month, as given in Table 1.

f. The average water content of the rain is derived by assuming that an air parcel, equal in vertical extent to the distance from sea surface to cloud base (i.e., equal to d), flows into the orographic cloud and is lifted wet-adiabatically from cloud base to within one-half of the distance d below the cloud top. Cloud-base mixing ratio is approximated from the Hilo radiosonde records (PST pp. 569—580), a tephigram being used to derive the total condensed water.

g. Column g lists the ratios of the total saltfall to the rainfall (c/b). This chloride concentration is thought to be equal to that which would be found in rains if one could catch all of the water falling from the showers as they move up the mountain slopes.

h. These computed chloride concentrations (a/f) are compared to the average of those observed (g). The reason for making this comparison is the idea that the rains are generated in certain ascending parcels of air. It is thought that the salt content of these parcels is equal to the average in the sub-cloud layer over the sea and that their water content equals that released in the wet adiabatic ascent of the parcel.

Figure 3 shows the relationship between the average of the chloride concentrations observed on the Saddle and Kulani Roads (Table 1, column g) and those estimated through the use of the rain-generating parcel model mentioned in h, above. (On October 19th through 21st, the Kulani Road gages were not yet in operation.)

3. Discussion of Figure 3

At first glance the relationship of the observed and computed chlorinities in this graph may seem poor. The values seem remarkably similar however, when one reviews the variability of many important factors involved.

For instance, if many rains begin upwind of gages 5 and 32 (Figure 2) and near the coast during a 24-hour period, the higher salinity drops which are the first to come from the showers (Turner 1955, Woodcock 1953) will fall before the showers pass over the sampling stations, thus causing these drops to be inadequately represented in the two lines of gages. The low-chloride rains of October 25 to 26 and December 2 to 3 may be due to this factor (see Figure 3 and the isoheytal maps pp. 587 and 589 PST).

Showers moving in directions not parallel to the lines of gages can also alter the assumed average pattern of the first larger drops falling in the lower-level gages and the smaller drops falling in gages successively further up the slope in the direction of shower drift. Such showers might serve to increase or to decrease the observed twenty-four hour average chlorinities such as those given in Figure 3.

On many occasions only one measurement of airborne salt was available for a 24-hour period. The data however show differences of two to three times in airborne salt in a day, thus adding a further potential error in the computed concentrations of Figure 3.

Errors can arise in the estimation of condensed water from uncertainties as to the time of occurrence of the most of the rain[1] and consequently as to which of the four daily radiosonde records to use in estimating cloud thickness and the amounts of condensed water. The average inversion altitude, as reflected in the drying of the air $\leq 50\,\%$, has been used here in estimating condensed water amounts, though if one knew the time of occurrence of most of the rain, it might be much more realistic to use only one of the radiosonde records as specifying the state of the lower atmosphere.

Leopold's suggestion of the possible existence of local convergence over the region of maximum rainfall (LEOPOLD 1949) may also be important here, though occasional observation from aircraft revealed no marked increase in cloud top altitudes in this region of the orographic cloud.

The presently most satisfactory explanation of the results on Figure 3 is one requiring the assumption that the major growth of the raindrops takes place in parcels of ascending air, and that in the drop growth process all of the salt particles in these parcels become dissolved in the rain waters. Alternative assumptions of fallout of all salt and condensed water in the whole cloud, or of washout of total cloud salt by rain formed in the parcels alone, produce computed salinity values which in all cases fall to the right of the forty-five degree line on Figure 3.

[1] The rain recorders should have been in continuous operation.

We might also suppose that the salt and water does not come from the sub-cloud parcels exclusively, but is fractionally extracted from most of the cloud in some accretion process such as that suggested by BOWEN (1950). If this occurs, then the relationship suggested by Figure 3 requires that this accretion process in each shower extract an amount of water and salt from the cloud which is approximately proportional to the cloud-base-to-inversion distance and to the weight of salt in the sub-cloud layer respectively.

Proportionalities such as these seem reasonable, but the sequence of events pictured in Bowen's model seems clearly inapplicable to the Hawaii orographic shower rains. For instance, WEXLER (1954) has shown that application of Bowen's model to the growth of marine aerosols in cumuli should result in an early fall out of the giant (10^{-9} gm) sea-salt particles as small raindrops, whereas the more numerous smaller (10^{-10} gm) particles should fall later in the shower as larger drops. Howver, WOODCOCK and BLANCHARD (1955) found that the initial drops falling at the beginning of a shower at cloud base were large and few in number and later Turner showed that the salt content of the large drops ranged from about 2×10^{-9} to 10^{-8} grams (see TURNER 1955, Figure 4, curves b). WOODCOCK and BLANCHARD (1955) also showed that the numbers of these drops per cubic meter of air approximated the numbers of the giant salt particles of the masses given, suggesting a growth mechanism which tended to conserve the number per unit volume of air as the giant nuclei grow to raindrop size. Thus if one assumes that the coalescense of many droplets containing smaller amounts of salt have chanced to become one drop whose salt content is equivalent to the mass of the larger sea-salt particles, he is faced with the problem of explaining the number correspondence mentioned above.

The purpose of emphasizing here the large amounts of salt in the large raindrops, however, is to suggest that the evidence is against the Bowen mechanism as one which is consistent with the results given in Figure 3, since the mechanism fails to account for some of the details of the character of the rains represented. On the other hand, the salt nuclei hypothesis of raindrop formation outlined by the author

(WOODCOCK 1952) and tested in collaboration with BLANCHARD (1955), does not conflict with Turner's observations (WOODCOCK and BLANCHARD 1955). It is pertinent to repeat here that this hypothesis led to the suggestion that the fraction of the rain and chloride which was not found near cloud base, should be found among the drops distributed up the mountain slopes by the winnowing action of the wind. The integrated total fall of salt and water on these slopes (columns b and c, Table 1), does indeed appear to be a rough summation of the total amount of these substances in the rain-generating parcel of air.

Entrainment of air from the orographic cloud into the shower-producing parcels has not been considered. An implication of Figure 3 is that entrainment into the parcels, if it occurs, does not greatly alter their relative salt and water contents.

Impactor samples of salt aerosols taken by JUNGE (PST pp. 535) near ground levels well within the orographic clouds, and during "drizzle", showed an almost complete absence of chloride among the "giant particles" (0.8 to 8 μ radius). This might be mistakenly interpreted as indicating that the rains had washed out all of the particles with which we are concerned here. However, within the cloud most of the giant sea-salt particles would have grown into cloud droplets larger than Junge's upper limiting size of 8 μ (KEITH and ARONS 1957), and thus would have fallen out in the 50 cm long "precipitation tube", before reaching the sampling surfaces of his impactor (JUNGE 1958).

The foregoing discussion of Figure 3 is not regarded as proof that the major growth of the raindrops occurs exclusively in parcels of sub-cloud air ascending in the orographic cloud. At this time, however, the author is unable to think of a more plausible notion. Later in this paper a further method for testing this idea in the future is outlined.

The mechanics of rain formation which can lead to the observational results given in Figure 3 and to those upon which the salt-nuclei raindrop hypothesis (WOODCOCK and BLANCHARD 1955) is based remain unknown to the author, though KOMABAYASI (1958) has made an interesting approach to the latter problem. Recent work by C. G. H. Rooth (unpublished) on an additional theoretical model, involving drop growth in air parcels having the form of spherical vortices, is producing some useful results. In the meantime, some of the implications of the present air-parcel idea of shower rain origin seem worth additional investigation here in an effort to mark out promising paths for further exploratory field work.

The author has long entertained the idea that parcels of air in which showers are to form may be identifiable in the tradewind stream over the sea, prior to their passage over the windward shore and into the orographic clouds. The following study supports

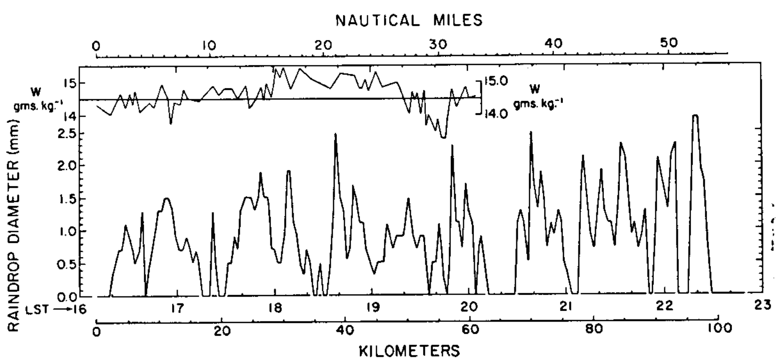

Fig. 4. The lower part of this graph gives the maximum drop diameter (± 0.1 mm) found on the drop-recorder tape, exposed at station 4 on Oct. 21, 1954, as a function of time. The distance scales represent the motion of the lower air (at 8.5 knots) during the time the rain recorder was operating. The upper part of the graph shows horizontal differences in mixing ratio which were taken from Figure 5. (A correspondence of upper and lower traces on Figure 4 is not to be expected.) See text for more explanation.

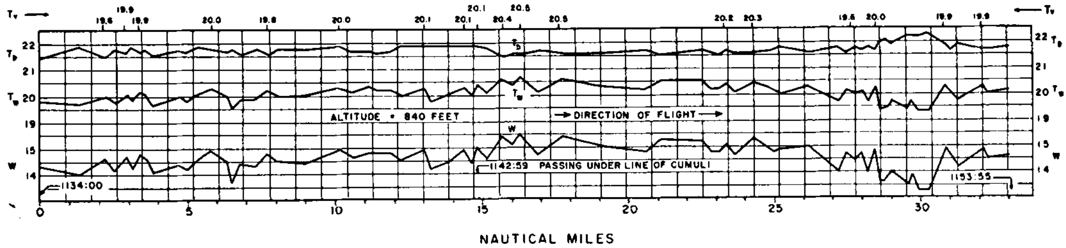

Fig. 5. Reproduction of some of Johnson's data (PST p. 498, Fig. 5) showing differences in the distribution of temperature and water vapor on Oct. 21, 1954, in a horizontal flight made about parallel to the surface wind and windward of Hawaii. The purpose here is to illustrate the effects of the differences in the amounts of vapor upon the virtual temperature when the sub-cloud layer is lifted above the saturation altitude. The numbers at the top of the figure were added to show the range of virtual temperatures which will exist in the moist parcels if the layer is lifted adiabatically to the 911 mb level. Note that the virtual temperature of these parcels exceeds that of the environmental air at the time (see Table 2).

this idea in a way which enables one to form some specific questions upon which to base suggestions for further work.

4. Identifying potential rain-forming air parcels

Concerning the idea of the existence of specific shower-producing parcels in the sub-cloud layer over the sea, it is interesting to ask how many showers fall each twenty-four hours, and what property differences in the layer might show a frequency of recurrence similar to that of the showers.

Unfortunately, there was only one day during the project when a rain recorder was in operation at a time when measurements were also made in the sub-cloud air over the sea and when the flight was made parallel with the surface wind.

On October 21, 1954, between 1610 and 2250 HST, a rain-recorder indicated about thirty-four showers passing station 4 (see map, Figure 1). Each increase in raindrop size, or each peak in recorded maximum size (see lower part of Figure 4) is counted as a separate shower, since there seems to be no clear physical basis for discrimination among them at this time.

Between 1054 and 1217 on the same day, wet- and dry-bulb temperature measurements were made in the lower air over the sea along a flight path parallel with the surface wind and windward of the sampling area on Hawaii (see PST p. 498). A part of the flight data is reproduced here in Figure 5 and at the top of Figure 4. The timing of these aircraft measurements was such that some of the air in which the flight was made would flow over the island sampling area during the rain-sampling period. The Hilo wind for the 300 m to 2,100 m layer, averaged 8.5 knots during the rain-sampling period (PST p. 570). Thus, about 57 nautical miles of air flowed over the Saddle Road during the rain-sampling interval (see distance scale on Figure 4).

Examination of Figures 4 and 5 shows that the factor which might significantly alter the stability of this lower air as it is forced up into the orographic cloud and one which varies spatially at frequent intervals in flight parallel with the wind, is the amount of water vapor.[1] It will be noted that there are 18 marked peaks in the mixing ratio (W) in the 33 nautical mile flight path. The vapor content and temperature of these moist air parcels was such that their virtual temperature, upon adiabatic lifting to 911 mb and higher, would exceed that of the environment at the time by at least 0.5 °C (see Table 2). Figure 6 shows graphically these excess temperatures, using the environmental conditions specified by the Hilo radiosonde and by Johnson's airplane sounding. These more unstable parcels of air from the sub-cloud layer should ascend

[1] The results of cross-wind flights by Johnson are not useful here because the rain recorders indicate the showers that occur along the line of flow of the trades, and not those that occur normal to them. It is noteworthy that the frequency of occurrence of horizontal differences in W in the sub-cloud air was not the same during the parallel-with-the wind flight on October 21, and cross-wind flights on other days (see PST, pp. 498, 501, 502 and 503). Measurements should have been made on both headings at about the same time and altitude on each of the days studied.

Table 2. Results of airplane sounding made by Johnson (PST p. 499) at 1218 to 1241 HST, on Oct. 21, 1954, over the sea a few miles southeast of Hilo. The pressures were derived from the altimeter readings, and the virtual temperatures were derived through the use of Table 72 of the 1958 Smithsonian Meteorological Tables. The columns marked "moist parcels" give the virtual temperatures of the dryest and the wettest of the 18 moist parcels indicated on Figure 4, assuming adiabatic ascent above the condensation lifting level. Note that temperature (T_V) excess over that of the environment (columns 6, 9, 10 and 11) becomes large only above about 1,020 m.

Altimeter reading	Johnson's Sounding					"Moist Parcels"		Hilo Radiosonde		
						dryest	wettest	interpolated values		
	P	T_D	T_W	W	T_V	T_V	T_V	1100 T_V	1700 T_V	2300 T_V
m	mb	C	C	gm kg^{-1}						
256	983	22.1	20.2	14.6	24.7					
348	972	21.0	19.8	14.7	23.6					
430	963	20.1	18.8	13.9	22.6					
470	958	20.2	17.9	12.8	22.5					
510	953	19.8	17.9	13.0	22.1					
560	948	19.5	17.0	12.0	21.6					
607	942	19.3	16.6	11.7	21.4					
665	936	18.6	17.0	12.5	20.8					
760	926	18.4	15.8	11.2	20.4	20.4	21.1	21.0	19.2	20.2
850	915	17.8	15.5	11.3	19.8	19.9	20.6	20.4	18.9	19.6
890	911	17.1	15.9	12.0	19.1	19.6	20.4	20.2	17.9	19.3
940	905	16.8	14.8	11.0	18.7	19.4	20.1	19.8	17.3	18.8
1,020	897	16.6	14.8	11.1	18.5	19.0	19.8	19.3	16.6	18.2
1,050	894	16.1	14.7	11.3	18.1	18.9	19.6	19.2	16.4	18.0
1,280	868	14.9	12.6	9.7	16.6	17.7	18.4	17.5	15.5	16.0
1,320	864	14.7	12.5	9.7	16.4	17.4	18.3	17.2	15.4	15.7
1,380	858	14.5	12.1	9.5	16.2	17.2	18.0	16.8	15.3	15.2
1,460	849	13.8	11.0	8.6	15.3	16.8	17.5	16.2	15.0	14.5
1,495	846	13.8	11.2	9.0	15.4	16.7	17.3	16.0	15.0	14.3
1,640	831	12.7	10.8	9.1	14.3	15.9	16.7	15.0	14.5	13.2
1,680	827	12.2	10.9	9.5	13.8	15.7	16.4	14.7	14.2	12.8
1,700	825	11.9	10.5	9.2	13.5	15.6	16.4	14.6	14.0	12.7
1,780	817	11.5	10.2	9.1	13.1	15.1	15.9	14.1	13.6	12.1
1,830	812	11.0	10.0	9.2	12.6	15.1	15.7	13.8	13.2	11.7
1,975	797	10.6	8.2	7.7	11.9	14.0	15.0	12.8	12.1	10.5
2,130	782	9.4	8.9	9.0	10.9	13.2	14.1	11.8	11.0	—
2,300	765	8.8	6.2	6.8	10.0	12.4	13.2	10.7	9.8	—
2,440	753	8.3	5.8	6.7	9.4	11.8	12.6	9.8	8.9	—
2,560	744	10.6	0.7	1.5	10.9	11.0	11.9	10.4	8.0	—
2,750	723	10.7	0.5	1.5	11.0	10.0	10.9	11.8	6.6	—
3,040	697	8.5	—0.9	1.4	8.7	8.3	9.3	—	9.0	

more rapidly in the orographic cloud than other parts of this layer. MALKUS (1954) has shown that virtual temperature excesses of 0.5 to 2 °C are commonly associated with the most rapidly ascending air in trade-wind cumulus clouds. It is assumed that it is within these moist parcels that the showers develop after the sub-cloud air passes up the windward slopes of the island and into the orographic cloud.

Thus, in the 57 nautical miles of air flow over station 4 on the Saddle Road, about 31 of these moist parcels should pass. Thirty-four showers were estimated from the rain-recorder tapes. The purpose here is that of simply emphasizing the rough similarity of the spatial distribution of showers and moist parcels (see Figure 4), and to point out that the parcels would have the highest virtual temperature in the clouds. We do not know the structure of the air which actually passed over the rain-recorder station. However, we do know that more than 75% of the 120 nautical miles of air measured by Johnson on the 21st showed structure similar to that represented at the top of Figure 4.

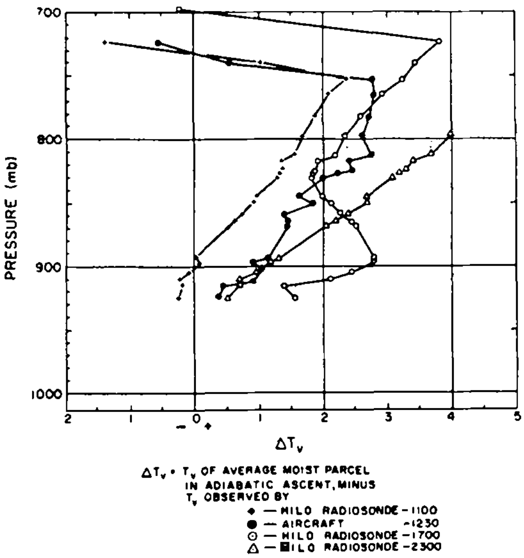

Fig. 6. Virtual temperature differences between the average moist parcel (Fig. 5) in adiabatic ascent and that within the lower atmosphere at various times during the observation period. Aircraft sounding made over sea about ten nautical miles southeast of Hilo.

5. Discussion of Figures 4 and 5, and Table 2

It may be argued that the difference between the virtual temperature of the "moist parcels" and that of the adjacent "dryer parcels" (a few tenths to one degree) seems small. It should be remembered, however, that as the lower air orographically ascends, the moist parcels will be the first to reach the condensation lifting level, and hence will be the first to experience the additional buoyancy as latent heat is released. The recurring showers, and the similarity of their number to that of the moist parcels present a picture of chain-like rain-forming air masses linearly imbedded within the wind stream passing over the island. This perhaps explains the cellular nature of the orographic cloud, particularly towards its seaward edge, as noted by Squires and Warner among the records from their numerous flights made within this cloud to determine the droplet size distribution and liquid water content (see PST, p. 487). Many more measurements of moist parcel number and shower number are needed however. One naturally wonders what the moisture structure of the sub-cloud layer might be in the absence of shower activity on the island and when known influencing factors such as the temperature inversion and wind characteristics seem favorable for showers.

It will be noted that Johnson has indicated a mixing ratio accuracy of $\pm$ 0.2 gm kg^{-1} as derived from his psychrometric measurements. This error is due primarily "to the inaccuracy in determining the correction for dynamic heating" (PST p. 496). We are largely concerned here with differences rather than absolute values in mixing ratio. Since air speed was constant, dynamic heating errors would also be constant. The wet- and dry-bulb temperature (and hence mixing ratio) differences encountered in flight are concluded theref re to be real.

Similar spatial differences in water vapor had been previously observed from ships and aircraft in trade-wind regions of the Atlantic and on the windward shore of one of the Hawaiian islands (see Figures. 7 and 8). It is thought that these features are common in the sub-cloud air of these and perhaps other latitudes. In fact the data on Figure 9 show that moist parcels are present in the lower wind stream a short time after continental air passes over the sea, though in this case it is thought that the moist regions are of very limited vertical extent.

Sensitive shielded mercury thermometers were used to make the measurements reported on Figure 9. Response time was 60 % full scale in seven seconds and thermometer error correction was applied to the nearest five-hundredths of a degree. Readings were made each thirty seconds at a fixed location on the

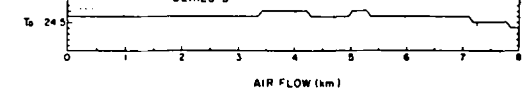

Fig. 7. Horizontal differences in the temperature and mixing ratio in the lower atmosphere of an Atlantic trade-wind area. It can be seen that these differences are very similar in frequency and amplitude to those presented in Fig. 4, 8 and 9. Table 3 and text give more information about these data.

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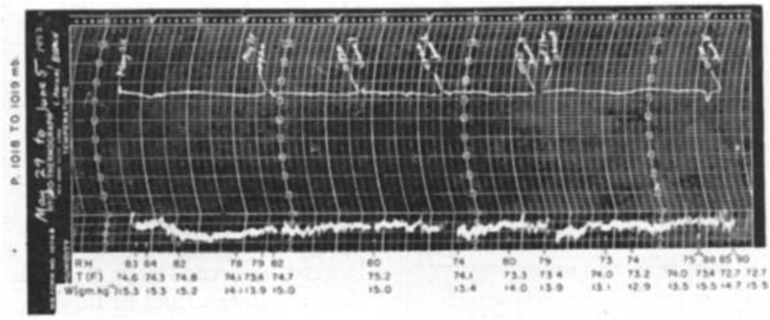

Fig. 8. One of five similar hygro-thermograph records from instrument exposed to trade winds at Lanikai Beach, Oahu, Hawaii. Location about 30 meters from windward shore, at site shielded from direct solar radiation and rain. For comparison, data from sling psychrometer measurements given in table below. Thermometer error corrected to nearest 0.1°, and times adjusted to error of the thermograph clock. Hygrothermograph shows short period RH changes of 4% to 10% with little dry temperature change. Mercury thermometers confirm these differences, when consecutive readings are made a few minutes apart (see results of last four measurements on table).

outer end of a pier near the Woods Hole laboratories, the passing air being metered with a recording anemometer.

The series two temperature measurements (Table 3 and Figure 7) were made at the bow of the research vessel Atlantis while it was in the Atlantic trade-wind area and moving windward. A sling psychrometer was used, and the thermometers were read each fifteen seconds. Radiation shielding was supplied by metal foil, and thermometer error corrected to the nearest one-tenth degree. The series three data were kindly supplied by Mr. A. F. Bunker of the Woods Hole Oceanographic Institution, from his aircraft measurements.

The effects of short-period variations in the thermal structure of the lower 3,000 m of the trade-wind atmosphere in altering the stability of the moist parcels (inadiabatic ascent), is clearly illustrated on Figure 6. A progressive

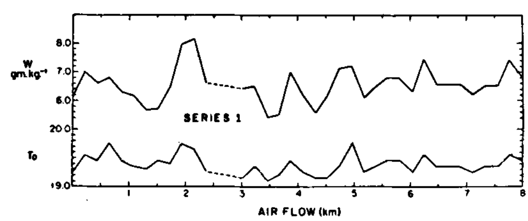

Fig. 9. Temperature and mixing ratio found within the wind stream shortly after air passed from land to water surface. See Table 3 and text for further information.

increase in the T_V difference within a short time and distance is apparent, showing the potential importance of almost continuous scanning of this part of the atmosphere in trying to understand events in the clouds which are imbedded therein.

6. Estimate of shower diameters using parcel method

If most of the water condensing within the ascending shower-producing parcels eventually falls out along the lines of gages on the mountain slopes, one should be able to estimate the average sizes of the showers from the data on Table 1 and from the number of showers indicated by the rain recorders. The apparent average shower diameter (S) is estimated as follows:

$$S = \frac{R\,10^3}{Whn} \qquad (1)$$

where R = average total rain; see Figure 2 and Table 1, column b (liters m^{-1})

W = total water condensed; Table 1, column f (gms kg^{-1})

h = vertical distance from sea surface to cloud base; Table 1, column d. (m)

n = shower number (counted as on Figure 4).

Table 3. **Additional data concerning observations given on Figures 7, 8 and 9**

Series	Date	Time zonal	Lat. N	Long. W	Alt. m	Surface Wind		Atmos. Pressure mb	Sea Surface Temp. C	Place	Fetch km
						Speed m sec^{-1}	Direction				
1	July 11, 1945	1400	41°31′56″	70°40′15″	3	7	320	1015	22.6	dock	19
2	Apr. 24, 1947	0630	20°38′	69°00′	4	3	90	1017	26.2	ship's bow	> 1,000
3	Nov. 14, 1958	1100	18°40′	65°50″	305	7	70	977	—	aircraft	> 4,000

Unfortunately none of the Project Shower data properly fulfill the requirements of equation (1). This is not surprising, since the program of observations was not designed to answer the questions posed. During the best single twenty-four hour observation period (Dec. 1—2, Table 1 and PST pp. 548 and 549), the rain-recorders missed more than eight hours. The two- and three-hour intervals of Nov. 7 and Dec. 2 and 3, are also uncertain because the time required to read the numerous rain gages was about one-half of the total sampling time. Thus, on Dec. 2, the rainfall in the Saddle Road gage number 5 (see Figure 2 and PST p. 514) represents the period 1414 to 1612, while the last gage, number 25, caught rains falling between 1509 and 1715 (see data file Pineapple Research Institute, Honolulu, Hawaii).

Using interpolations and extrapolations of the rain gage and rain-recorder data to cover the unknown time intervals, shower diameters of from 1,700 to 4,100 meters were computed for the above dates, using equation (1).[1] This diameter range is consistent with the few individual showers distinguishable in the liquid water records obtained in the orographic cloud by Squires and Warner (PST, see especially Figure 12 and pp. 487—489). Also, the Hilo rawinsonde data indicate in general a sufficient air flow inland to transport air parcels of the number and size required. Examination of the rain-recorder records shows however that variability in shower activity with time makes the validity of extrapolations or interpolations very uncertain.

Thus the major usefulness of equation (1) at this time is to point out that it constitutes a further means of testing the shower-parcel idea, when applied to data obtained during a properly designed observation program.

7. Conclusions

The idea that the showers originate in specific moist parcels of air enables one to advance tentative explanations for the following characteristics of Hawaiian orographic rains which have been revealed by the Project Shower data.

1. Chloride concentration
2. Shower frequency
3. Total water content
4. Horizontal dimensions

This result suggests that these rains form in units of air within the trade wind stream which may be identifiable prior to their arrival over the land. Despite the limited extent of some of the data supporting this idea, a reasonably consistent shower model has evolved. The importance in meteorological studies of locating shower-forming air before the shower occurs, makes further work seem clearly worthwhile. Prior location would of course be a forecasting aid and would simplify and make more economic studies of the effects upon shower production of artificially altering the nuclei population and other characteristics of potential shower-producing air parcels.

Since the chloride and water contents of Hawaiian rains seem to be explicable through

[1] It will be noted that the drop maxima, shown by the peaks on rain records such as Figure 4, are represented by n in equation (1) as if individual showers contributed equal amounts of rain to the lines of gages. It is clear however that these showers are widely different in intensity at any one location (e.g. PST p. 545). The high-rate rains have larger drops and presumably briefer duration, while the low-rate rains have smaller drops and presumably longer duration. Thus an equal value for R, in equation (1), can result from a 30 mm hr^{-1} rain lasting three minutes or a 3 mm hr^{-1} rain of thirty minutes duration.

the use of the moist-parcel idea, the application of this idea to rains in other areas, becomes a question worth consideration.

The parcel idea suggests that orographic shower frequency is related to the frequency of occurrence of certain moist parcels having virtual temperature excesses over those of the environment comparable to or exceeding those shown on Figure 6.

The occurrence of orographic showers in regions such as Hawaii should be predictable from measurements made within the cloud and sub-cloud layers of the lower atmosphere which are soon to pass over the area concerned. Horizontal runs and vertical soundings by aircraft, similar to those made by Johnson, are best; their number and extent depending upon the variability with time, distance and altitude of virtual temperature, mixing ratio, and perhaps other factors such as wind shear.

Figure 8 indicates that the moist air parcels of higher levels probably extend to within a few meters of the sea surface. If so, a simple means of testing them as a source of showers would be to set up a line of observing stations along the coast normal to the dominant winds and windward of a network of recording rain gages. Thus one could continuously scan the surface air two-dimensionally (or perhaps three-dimensionally using towers) for moist parcels and for showers. Frequent local radiosonde and rawinsonde ascents would also be needed as indicated in the present study.

Relatively long term field programs should be initiated at favorable locations, with the purpose of understanding and perhaps exploiting the relationships indicated here between certain properties of the air stream and the precipitation resulting when this air is subsequently lifted.

Acknowledgements

This paper is one of the results of Project Shower, a international cooperative field study to which many persons and organizations contributed (Squires 1955). Without their simultaneous efforts, focused upon the complex of interrelated events often too simply termed "orographic showers", the present work could not have been performed. The author's co-workers, Mr. D. C. Blanchard and Mr. Claes Rooth contributed to this work through generous critical readings and discussions.

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