Some Measurements in the Orographic Cloud of the Island of Hawaii and in Trade Wind Cumuli

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Abstract

Aircraft observations were made of the liquid water content and droplet spectra in the orographic cloud of the windward (eastern) side of the Island of Hawaii and in trade wind cumuli offshore. The orographic cloud showed a number of remarkable features, some of which can be related to its mode of formation and to its general behaviour.

1. Introduction

During Project Shower, from October to early December 1954, measurements were made of the liquid water content and droplet spectra of clouds near Hilo, the capital of the Island of Hawaii, the south-easternmost of the Hawaiian Islands (Figs. 1 and 2). Observations were taken in trade wind cumuli over the sea off Hilo and in the orographic cloud which usually forms on the eastern slope of Hawaii when the trade wind blows. More importance was attached to the measurements in the orographic cloud, for the rain from it was being studied simultaneously by other participants in Project Shower.

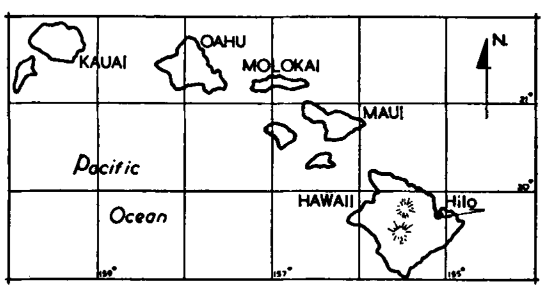


Fig. 1. The Hawaiian Islands.

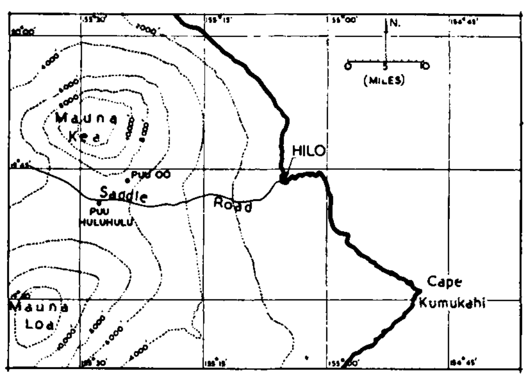


Fig. 2. Eastern Hawaii, the site of Project Shower.

2. Description of the orographic cloud

When the trade wind was fairly strong, the orographic cloud usually reached unbroken from the coast, or a mile or so seaward of it, right up to the Saddle between the two volcanoes Mauna Kea and Mauna Loa (see Fig. 2). Its top coincided with the base of the trade wind inversion. Fairly typical examples of the cloud system are shown in Photos 1 and 2. At the coast the top was most often around 6,000 ft., although on one day, December 2,

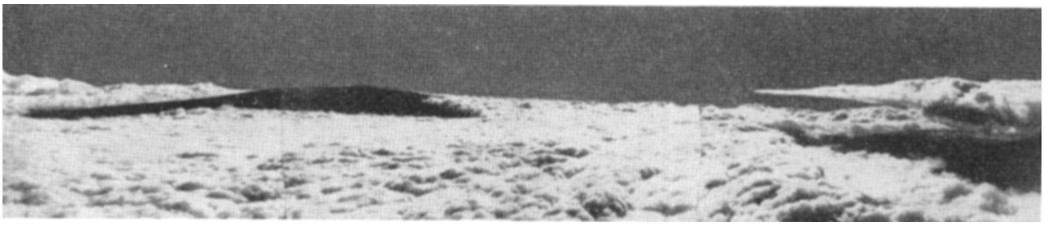
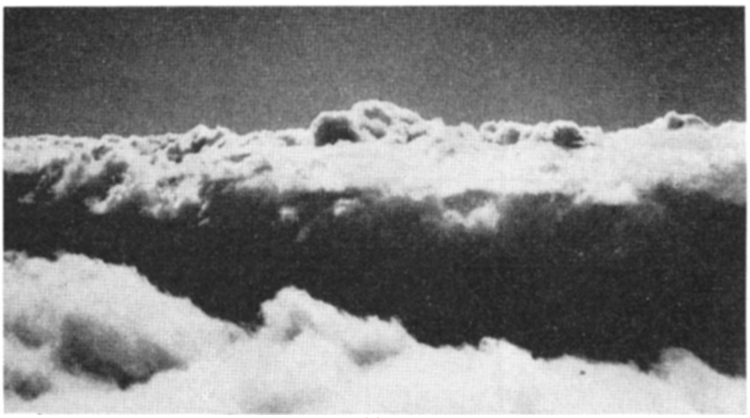


Photo 1. The orographic cloud over the land on 6 November 1954. The photograph was taken at 1610 hours looking west from an altitude of 10,000 ft when the aircraft was about 10 miles west of Hilo. Mauna Loa, left centre; the southern slope of Mauna Kea into the Saddle is just visible on the right. The broad cloud field beyond the Saddle is not a part of the orographic cloud; the clear lane in the Saddle between the two cloud masses cannot be discerned here.

(a)

(b)



(c)

Photo 2. The top photograph shows the seaward cloud, on 7 November 1954, looking east from a height of 10,500 ft, when the aircraft was just over the coast at 1454 hours. The middle photograph shows the orographic cloud, looking west towards the mountains, from the same position and at the same time. The lower photograph shows the clear lane in the Saddle area which on this occasion was about 2 miles wide and ran across from Mauna Loa to Mauna Kea without a break. The camera was facing approximately south-west when this photograph was taken at 1505 hours from an altitude of 10,500 ft. at a position a few miles east of the Saddle.

it was at 11,000 ft. At the Saddle the top was usually a little over 2,000 ft. above ground level, that is, about 8,500 ft. above sea level. Cloud base at the coast was equal to that of the seaward cumuli, which were most frequently based at 2,000 to 3,000 ft. The height of the base above sea level increased slowly at first as the cloud approached the mountain, until at some 10 miles from the coast the cloud appeared to touch the ground. However, observations on the ground showed that the cloud rarely came lower than 50 ft. anywhere on the mountain slope, at least during the day. The cloud sheet lay around the upper flanks of Mauna Kea and Mauna Loa, though on the Mauna Kea slopes in the vicinity of the cinder cone Puu Oo it did not run right up to the mountain slope, but broke up into dissolving flocks a mile or short of it.

The nature of the top surface of the orographic cloud varied somewhat from day to day. On some days, it was quite smooth in the coastal region, but had a bubbly appearance towards the Saddle. On others, there were small irregularities up to one to two hundred feet in height near the coast, with rather larger irregularities towards the Saddle. Sometimes the transition between the relatively smooth cloud top of the coastal region and the more irregular cloud top of the Saddle region was fairly sharp. This sharp transition, when it occurred, was associated with a sudden increase in the slope of the cloud top towards the Saddle.

Near the Saddle, the irregularities in the top surface of the cloud were commonly several hundred feet. In the Saddle itself, the top surface descended sharply at an average slope of perhaps one in one; its general appearance here was that of evaporating strato-cumulus. The orographic cloud terminated usually a mile or so west of the cinder cone Puu Huluhulu, the base then being 100 to 200 ft. above the ground. In the afternoon the western side of the Saddle was filled by a mass of cloud of quite different character. Its base was comparatively sharp at 200 to 300 ft. above ground, and its top was always higher than that of the orographic cloud. It terminated in the Saddle in a vertical wall, the detailed structure of which resembled that seen in the sides of an active cumulus. The top was moderately level with irregularities of less than a thousand feet. Its whole appearance indicated that it formed in a zone of air which was rising vertically at a moderate velocity and it appeared to be quite turbulent. This cloud was absent in the morning. Between the two cloud masses there was always a clear lane some two miles wide running across the Saddle close to and in the direction of the line joining the two peaks. Sometimes this lane ran clear across from the upper slopes of Mauna Kea to those of Mauna Loa, but more often cloud blocked off the end towards Mauna Loa some five miles south of the Saddle road.

On most occasions two regions could be distinguished during flights through the orographic cloud. The dividing line between these regions was usually about half-way between the coast and the Saddle. In the upper region near the Saddle, the cloud seemed visually to be of very uniform consistency, and there was little or no turbulence. In the lower region the cloud, although stratiform when seen from above, as seen from within became more and more cumuliform in the direction of the coast and the turbulence increased. Near the coast, distinct cumuli appeared with clear spaces between them, but their tops were still embedded in the stratiform cloud above. This change in the character of the cloud is indicated clearly in several of the liquid water content traces.

It will be noticed that the tendency for the cloud to become more cumuliform and turbulent towards the coast belies the appearance of its top surface as described earlier. An inspection of the upper surface would usually have led one to expect a more cumuliform and turbulent region towards the Saddle, contrary to what was actually found during the flights through the cloud.

3. Observational procedure

On the days on which the orographic cloud was studied, the flight procedure consisted initially of a climb in clear air between the seaward cumuli some ten miles east of Hilo to a height somewhat above cloud top. During the climb, measurements were made of temperature and humidity. The aircraft then flew in towards the Saddle, often climbing on the way to keep above the cloud. On arrival over the Saddle area a sounding was made while the aircraft circled down to as low a height as the pilot considered safe. This height depended on the width of the clear lane and on turbulence,

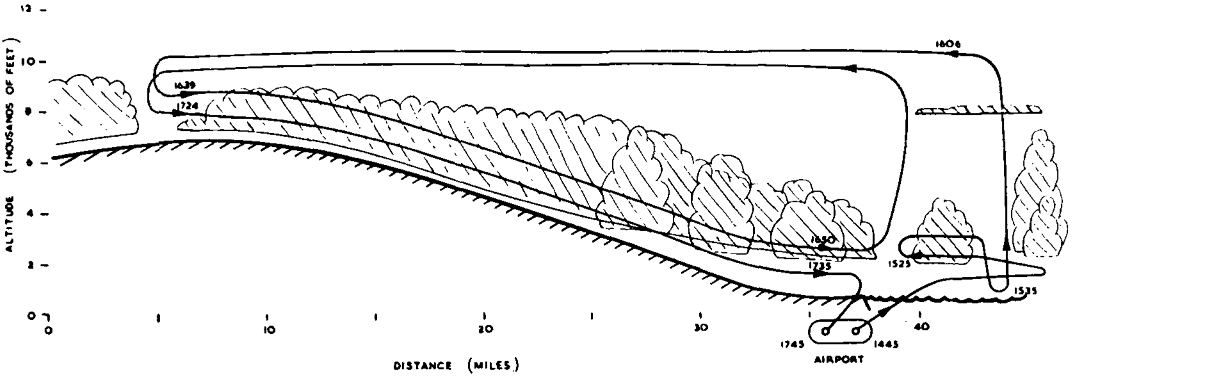


Fig. 3. Typical flight path on a day when runs were made through the orographic cloud at ground clearances of 2,000 and 1,000 ft. (Actually, for the flight on 6 November 1954 between 1445 hours and 1745 hours local time.) The flight commenced with two runs through a small cumulus over the sea, followed by a temperature and humidity sounding in clear air from the sea surface to 10,000 ft.

which was sometimes severe near the ground, but the ground clearance was seldom reduced below 500 ft. As the volcano slopes are gradual and uniform it seemed best to make the observing run through the orographic cloud at constant ground clearance as determined from a radar altimeter. It was found possible to hold the ground clearance to within 100 ft. of the desired value most of the time. Most often, runs were made at 1,000 and 2,000 ft. above the ground; on 2 December, the day when the cloud was much deeper than usual, they were made at 2,000, 4,000 and 6,000 ft. ground clearance. The aircraft track commenced in the clear lane and ran through Puu Huluhulu to Hilo Airport. It thus passed roughly over the line of the Saddle road. The indicated aircraft speed was held at 120 knots during the whole run resulting in a rate of descent or roughly 700 ft. per minute. At the completion of a run through cloud a climb was made in clear air off the coast and the procedure was repeated. The flight path for a typical run and a typical cloud configuration are shown diagrammatically in Fig. 3.

Observations in seaward cumuli were made in horizontal passes, usually at 500 ft. intervals of height, and in alternate directions. On most occasions a temperature and humidity sounding was performed in the vicinity of the cloud being studied.

4. Apparatus

(a) *Cloud droplet spectra*

The equipment used for measuring cloud droplet spectra has been described by Squires and Gillespie (1952). This method uses a glass rod 3 mm in diameter which is exposed to the cloud outside the co-pilot's window for about a thirtieth of a second. The volume of air sampled by the rod is about 50 cc. The rods were coated with a layer of soot.

The calibration of this method will be described elsewhere. At the speeds used, in the drop diameter region $d = 200\mu$ down to $d = 20\mu$ the ratio of the diameter of the hole in the soot layer to that of the drop is about 4, decreasing slowly with drop size. Below $d = 20\mu$, the ratio begins to decrease much more rapidly, reaching a value close to 1 at $d = 2\mu$. Above $d = 20\mu$, the probable error of the method is about 5 % in diameter; below $d = 15\mu$, the probable error appears to be about 15 %.

(b) *Liquid water content*

The instrument used for measuring cloud water content has been described by Warner and Newnham (1952). It depends for its operation on the effect of moisture on the electrical resistance of paper. A continuous record of liquid water content is obtained by measuring and recording the electrical resistance of a paper tape which has been moved past a narrow slit, open to the airstream, where it is moistened by the cloud droplets. The instrument collects more than 90 % of the liquid water for the drop size distributions encountered in Hawaiian clouds. By a suitable choice of tape speed, liquid water contents ranging from 0.05 to 5 gm m^{-3} can readily be measured. The accuracy is considered to be of the order of $\pm$ 20 %, and the instrument is capable of recording liquid water variations extending over a few hundred feet. Narrow regions of liquid water may be detected but their magnitude is generally not faithfully recorded, due to smoothing in the instrument as described by WARNER (1955). For example, in a cloud of average liquid water content 1 gm m^{-3}, a peak 100 ft. across rising to 2 gm m^{-3} would generally be indicated by a peak broadened to 400 ft. and of 1.4 gm m^{-3} maximum value.

(c) *Synchronization of the data*

The chart recorder used to record liquid water content was also used to obtain traces of pressure altitude as a function of time, and one-minute time marks were similarly recorded. In addition the time marker pen could be actuated simultaneously with the exposure of a cloud droplet sampling slide. Errors of timing of up to three seconds arose from various sources. This must be borne in mind when the liquid water contents found from the droplet spectra observations are compared with the continuous trace of liquid water content.

Table 1. Cloud droplet spectra 2 November 1954

See fig. 8 for positions and heights of the samples

Symbols

S = identification of sample; d_m, d_1, d_2, d_3, d_M = minimum, first quartile, median, third quartile and maximum droplet diameters in microns respectively;

n = concentration of droplets cm^{-3};

w = liquid water content g m^{-3} deduced from spectra

S	d_m	d_1	d_2	d_3	d_M	n	w
Orographic cloud at a ground clerance of 1,000 ft.							
a	5	14	21	31	130	17	0.38
b	18	31	34	37	52	24	0.52
c	12	28	36	39	52	21	0.47
d	18	33	36	40	45	7	0.17
e	5	11	15	22	39	40	0.13
f	5	8	10	12	21	56	0.05
g	5	7	11	19	39	135	0.32
h	5	11	12	29	72	35	0.31
i	15	20	21	24	28	58	0.33
j	9	19	22	24	39	52	0,31
k	25	32	34	36	165	20	0.64
l	5	21	27	39	168	17	0.52
m	21	29	42	49	91	3	0.19
n	5	29	44	60	121	6	0.59

5. Results

(a) *Cloud droplet spectra*

Tables 1 to 6 give the results of the measurements in the orographic cloud; tables 7 to 13 give the results for seaward cumuli. The spectra are specified by giving the values of the first quartile, median and third quartile diameters, and the maximum and minimum diameters. In addition, the total droplet concentration and the liquid water content deduced from the spectra are given. The maximum and minimum diameters are those found in a sample of about 30 cc of air. The minimum diameters are only approximate, because a rather large interval was used in evaluating these broad spectra, namely 14.7 microns in hole diameter. This corresponds to a droplet diameter interval of about 3.5 microns on the average. As a result of the decrease in ratio of hole diameter to

Table 2. Cloud droplet spectra 6 November 1954

See fig. 9 for positions and heights of those samples which are identified by a lower case letter*

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Orographic cloud at a ground clearance of 2,000 ft.							
a	5	12	17	24	35	79	0.40
b	9	16	20	24	39	89	0.50
c	12	17	22	26	39	153	0.96
d	5	11	15	22	32	28	0.09
e	5	11	14	18	28	50	0.12
f	5	12	15	19	35	81	0.20
g	No droplets found						
h	»	»	»				
i	»	»	»				
j	9	14	17	24	28	29	0.13
k	No droplets found						
l	»	»	»				
Orographic cloud at a ground clearance of 1,000 ft.							
a	9	12	15	17	42	98	0.30
b	9	10	11	12	42	210	0.23
c	9	12	14	15	21	115	0.17
d	5	7	8	10	18	325	0.12
e	No droplets found						
f	»	»	»				
g	9	12	14	15	25	222	0.32
h	5	10	13	17	28	220	0.33
i	No droplets found						
J*	9	9	11	12	21	367	0.22
K*	5	5	6	9	39	374	0.26

* Samples identified by upper case letters: position of sample on liquid water trace not known.

Table 3. Cloud droplet spectra 7 November 1954

See fig. 11 for positions and heights of the samples

p. m.

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Orographic cloud at a ground clearance of 1,000 ft.							
a	5	29	36	37	118	9	0.29
b	5	30	36	40	118	8	0.26
c	5	12	33	52	88	3	0.15
d	18	34	39	47	142	16	0.89
e	18	46	53	60	100	1	0.12
f	5	55	75	89	115	4	0.28
g	12	46	53	55	100	4	0.37
h	15	40	52	57	106	10	0.75
i	25	43	52	57	130	7	0.70
j	9	33	35	59	130	5	0.32
k	5	9	15	19	42	11	0.05
l	18	40	53	63	121	3	0.35
m	5	15	23	35	106	9	0.34
n	9	32	40	55	91	6	0.23
o	9	36	53	60	84	4	0.27
p	18	31	33	36	78	18	0.45
q	18	26	31	33	42	37	0.55
r	5	11	15	16	28	82	0.16
Orographic cloud at a ground clearance of 2,000 ft.							
a	15	28	35	40	55	24	0.58
b	18	31	36	39	52	16	0.41
c	21	33	36	39	59	10	0.32
d	18	42	49	53	69	5	0.33
e	12	19	20	52	130	5	0.35
f	21	42	46	49	62	13	0.73
g	12	14	18	29	130	9	0.16
h	5	12	18	23	84	3	0.07

Table 4. Cloud droplet spectra 30 November 1954

No corresponding figure shown

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Orographic cloud at a ground clearance of 2,000 ft. Heights of samples range from 8,500 ft for sample A to 4,400 ft for Sample J.							
A	9	10	11	12	18	121	0.11
B	5	24	28	30	69	53	0.62
C	5	14	19	40	69	21	0.38
D	5	12	16	19	68	7	0.02
E	18	46	49	53	72	8	0.44
F	15	28	36	53	69	4	0.20
G	12	25	39	45	72	3	0.16
H	12	21	25	29	39	23	0.19
I	9	26	27	29	42	46	0.55
J	5	11	15	19	25	67	0.27

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Orographic cloud at a ground clearance of 1,000 ft. Heights of samples range from 7,800 ft for sample A to 5,500 ft for sample I.							
A	12	26	28	40	65	16	0.36
B	9	13	14	19	42	21	0.07
C	18	31	33	36	42	41	0.63
D	12	23	29	33	42	51	0.53
E	18	21	28	30	55	14	0.16
F	9	23	26	29	52	39	0.49
G	5	8	13	17	39	74	0.48
H	9	10	11	16	49	73	0.11
I	9	9	10	11	25	113	0.12

Table 5. Cloud droplet spectra 2 December 1954

See fig. 12 for positions and heights of those samples which are identified by a lower case letter*

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Orographic cloud at a ground clearance of 6,000 ft.							
a	9	19	34	67	109	2	0.16
b	21	21	22	30	62	2	0.01
c	9	51	59	76	100	1	0.12
d	9	22	38	52	127	4	0.26
e	12	44	54	64	148	4	0.48
f	9	24	38	50	159	4	0.37
g	No droplets found						
H*	9	17	25	41	124	7	0.27
I*	25	41	69	82	97	3	0.52
Same cloud at a ground clearance of 4,000 ft.							
a	28	46	50	57	84	3	0.26
b	12	26	47	63	159	2	0.35
c	45	54	61	64	145	2	0.33
d	62	79	93	114	159	1	0.50
e	25	27	29	33	142	3	0.34
f	28	48	52	58	145	3	0.31
g	35	48	51	70	91	3	0.39
h	15	37	51	67	136	5	0.59
i	12	30	39	51	103	3	0.43
j	9	20	30	48	127	2	0.14
k	5	16	28	48	139	13	0.39
l	9	19	27	40	84	24	0.57
m	No droplets found						
n	» » »						
o	» » »						
p	» » »						
Same cloud at a ground clerance of 2,000 ft.							
a	15	27	37	49	75	2	0.07
b	5	10	13	15	145	3	0.19
c	28	47	53	69	118	2	0.27
d	9	17	23	47	100	2	0.26
e	5	15	23	30	130	3	0.19
f	25	40	46	52	106	4	0.33
g	5	12	14	16	25	6	0.01
h	9	27	27	34	52	5	0.08
i	9	22	26	32	62	8	0.13
j	5	14	16	27	32	7	0.01

* Samples identified by upper case letters: these two samples were taken just offshore after the liquid water content meter had been stopped.

Table 6. Cloud droplet spectra 3 December 1954
See fig. 13 for positions and heights of those samples which are identifiied by a lower case letter*

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Orographic cloud at a ground clearance of 2,000 ft.							
a	No droplets found						
b	15	17	20	27	45	11	0.08
c	18	31	33	37	65	5	0.13
d	18	32	47	72	145	3	0.93
e	15	26	28	32	49	56	0.77
f	5	14	18	22	68	15	0.11
g	5	20	24	26	35	57	0.44
h	5	12	14	16	18	49	0.07
i	No droplets found						
j		»	»	»			
k		»	»	»			
l		»	»	»			
m	5	10	14	18	130	6	0.19
n	No droplets found						
Same cloud at a ground clearance of 1,000 ft.							
a	9	27	32	38	124	13	0.75
b	5	25	33	52	168	2	0.63
c	12	24	28	33	159	9	0.30
d	9	15	18	19	112	14	0.20
e	12	35	63	76	124	5	0.68
f	12	35	52	59	130	10	0.86
g	12	25	46	69	88	2	0.17
h	28	38	45	52	115	3	0.17
i	18	28	33	38	62	6	0.15
J*	9	15	18	21	32	43	0.17
K*	5	11	14	17	42	33	0.10

Table 7. Cloud droplet spectra 23 October 1954
See fig. 15 for positions of those samples which are identified by a lower case letter*
Successive passses through a moderate seaward cumulus at various levels

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Height (ft): 3,250							
a	15	17	19	20	28	93	0.34
b	15	17	19	21	28	44	0.18
c	No droplets found						
d	18	25	27	29	32	99	1.00
e	5	14	16	21	35	59	0.22
Height (ft): 4,250							
a	No droplets found						
b		»	»	»			
c	15	21	23	27	32	64	0.35
d	25	29	31	34	42	38	0.66
e	5	11	18	28	39	50	0.31
f	No droplets found						
Height (ft): 4,750							
a	No droplets found						
b	25	28	30	31	35	58	0.86
c	15	26	28	32	42	74	1.06
Height (ft): 5,250							
a	28	—	80	—	154	0.3	0.34
b	No droplets found						
c	5	21	30	41	55	17	0.37
d	5	12	17	20	39	36	0.12
e	28	32	34	36	42	54	1.14
Height (ft): 5,750							
A*	9	35	40	41	52	38	1.03
B*	No droplets found						
C*		»	»	»			
D*	5	13	21	32	45	64	0.65
E*	5	30	31	33	42	107	1.60
F*	32	34	35	36	42	93	0.20
Height (ft): 6,250							
A*	5	21	25	34	52	28	0.46
B*	9	14	16	18	35	42	0.11
C*	9	24	31	39	55	24	0.57
D*	5	23	28	37	59	75	1.40
E*	9	23	28	34	49	4	0.25
F*	9	16	20	25	39	5	0.03

* Samples identified by upper case letters: position of sample on liquid water trace not known.

Table 8. Cloud droplet spectra 2 November 1954
No corresponding figure shown
Small seaward cumulus subsiding during sampling

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Height (ft): 2,500							
A	5	10	13	19	62	21	0.08
B	5	9	13	19	52	215	0.64
C	5	14	17	19	25	147	0.36
D	9	15	17	19	32	71	0.19
E	5	12	16	23	32	86	0.34
F	5	8	12	19	35	29	0.09

Table 9. Cloud droplet spectra 6 November 1954
See fig. 16a for positions of the samples

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Small seaward cumulus. Height (ft): 1,800							
a	5	9	11	13	21	63	0.05
b	9	17	18	19	28	43	0.14
c	9	16	17	19	35	55	0.18
d	15	17	18	19	21	133	0.45
e	15	17	18	19	32	117	0.44
f	12	17	18	19	28	74	0.25
g	12	18	20	22	28	82	0.38

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Similar cumulus with some light rain. Height (ft): 1,800							
h		No droplets found					
i	12	16	19	21	28	85	0.37
j	9	16	19	21	28	28	0.11
Similar cumulus with some light rain. Height (ft): 2,400							
a	15	24	27	31	32	122	0.34
b	9	16	21	27	32	94	0.57
c	15	25	27	29	35	75	0.30
d	21	25	27	29	35	87	0.94
e	15	23	25	28	35	80	0.72
f	5	13	18	23	39	52	0.24
g	9	17	21	25	35	24	0.16
Similar cumulus, with light rain. Height (ft): 2,400							
h	9	17	20	24	35	30	0.17
i	9	20	22	25	35	72	0.47
j	25	27	29	31	35	85	1.10

Table 10. Cloud droplet spectra 7 November 1954

No corresponding figure shown

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Isolated layer of stratus near coast. Height (ft): 5,100							
A	15	30	35	40	62	24	0.62
B	5	6	14	21	32	9	0.03
C	28	33	35	38	59	12	0.35
D	18	41	48	52	72	6	0.41
E	18	34	37	42	84	14	0.53
F	15	23	28	32	42	36	0.46
G	5	9	12	15	25	66	0.09

Table 11. Cloud droplet spectra 26 November 1954

See fig. 16b for positions of those samples which are identified by a lower case letter*

S	d	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Small seaward cumuli. Height (ft): 4,000							
A*	9	14	15	16	18	171	0.31
B*	5	12	14	15	18	97	0.15
c	5	12	14	15	25	150	0.23

* Sample identified by an upper case letter, taken in the first run at 4,000 ft: positions on liquid water trace not known.

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Small seaward cumuli Height (ft): 5,000							
a		No droplets found					
b		»	»	»			
c	5	14	17	19	28	73	0.20
d	5	10	13	16	32	26	0.04
e	5	11	15	18	25	57	0.14
f	5	8	11	15	21	12	0.01
g	5	10	14	18	28	82	0.16
h		No droplets found					
i	5	12	17	20	28	67	0.20
Small seaward cumuli. Height (ft): 6,000							
a		No droplets found					
b	18	19	24	28	35	111	0.84
c	12	23	25	28	39	101	0.88
d		No droplets found					
e		»	»	»			
f		»	»	»			
g	15	25	27	29	35	176	1.75
h	12	25	27	28	35	137	1.36
i		No droplets found					
Moderate seaward cumulus (fairly turbulent, with light rain towards end of run). Liquid water trace not shown. Height (ft): 7,000							
A	12	21	26	29	49	66	0.66
B	9	21	25	28	62	79	0.74
C	9	22	26	32	45	58	0.71
D	18	25	28	30	49	82	1.00
E	9	20	26	31	42	71	0.71
F	12	19	23	28	42	121	2.14
G	12	22	27	31	35	57	0.62
H	12	25	28	31	39	128	1.50
I	15	25	29	31	42	62	0.79
J	15	28	31	34	42	164	2.69

Table 12. Cloud droplet spectra 1 December 1954

See fig. 17 for positions of those samples which are identified by a lower case letter*

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
A seaward cumulus. Height (ft): 5,600							
a	5	24	28	32	39	107	1.29
b	12	23	27	30	39	20	0.20
c	15	26	29	32	39	20	0.25
d	9	15	23	28	39	14	0.11
e	12	21	26	29	39	10	0.10
f	12	25	29	32	42	20	0.26
g	12	23	26	27	42	5	0.06
h	5	9	16	25	35	13	0.05

* Samples identified by an upper case letter: position of sample on liquid water trace not known.

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Several small cumuli. Height (ft): 5,600							
i	5	12	15	23	35	24	0.09
j	15	24	28	31	42	42	0.50
k	15	26	29	32	42	27	0.37
l	5	15	19	23	32	8	0.04
m	12	26	29	32	42	16	0.21
n	12	20	24	28	39	17	0.16
o	12	19	26	29	35	11	0.10
p	9	20	23	28	35	27	0.23
q	12	24	27	30	39	21	0.23
Several small cumuli. Height (ft): 3,800							
a	9	14	16	18	21	13	0.28
b	12	21	24	25	32	88	0.61
c	12	20	22	25	32	72	0.78
d	9	18	22	26	32	34	0.20
e	12	20	23	25	32	25	0.16
f	12	21	24	26	35	60	0.43
G*	15	19	22	24	28	59	0.32
H*	15	19	22	25	32	48	0.27
i	15	19	22	25	32	95	0.56
J*	9	17	18	20	28	21	0.07
K*	5	17	18	19	25	32	0.09
l	12	19	21	24	28	73	0.39
M*	5	10	12	13	25	55	0.07
n	12	15	17	19	25	83	0.25
O*	15	19	21	23	35	120	0.62
P*	9	15	18	23	35	69	0.29
Q*	15	17	18	20	32	24	0.09
r	5	11	16	18	25	32	0.08
S*	9	17	18	19	25	37	0.11
T*	5	10	13	16	21	14	0.02
u	5	12	16	20	35	50	0.14
V*	9	14	17	21	42	101	0.35
W*	9	14	17	19	25	53	0.14
x	12	17	19	21	28	81	0.29
Line of small cumuli about 1,000 ft in depth. Height (ft): 3,200							
a	12	16	19	22	28	115	0.46
B*	9	14	16	18	39	74	0.18
c	9	15	17	19	32	34	0.10
d	5	14	16	18	39	29	0.07
e	9	14	15	16	21	188	0.32
f	5	10	12	15	28	20	0.02

Table 13. Cloud droplet spectra 3 December 1954
No corresponding figure shown

S	d_m	d_1	d_2	d_3	d_M	n	w
(for meanings, see table 1)							
Several small seaward cumuli, bases 3,000 ft; tops 4,000—4,500 ft. Height (ft): 3,900							
A	5	11	15	18	28	8	0.02
B	5	11	15	18	25	26	0.05
C	9	17	18	20	25	199	0.70
D	5	14	17	22	28	42	0.15
E	12	20	21	23	25	52	0.26
F	5	18	23	27	55	108	0.80
G	15	21	23	25	32	81	0.54
H	5	15	24	27	52	53	0.37

droplet diameter with decreasing drop diameter, the interval of droplet diameter becomes slightly larger at very small sizes. As a result, the smallest droplets are all grouped in the interval $3.1\,\mu < d < 7.1\,\mu$. When, therefore, droplets in this lowest range were observed, the minimum diameter is quoted as 5μ.

In the tables the samples are identified by a letter. Lower case letters indicate that there is a corresponding point plotted on the liquid water content trace, identified by the same letter in Figs. 7 to 17 inclusive. Upper case letters indicate the contrary — either because the liquid water content trace is not shown, or because the position on the trace corresponding to the sample is not known. In these tables, as elsewhere, the heights quoted are those read from a pressure altimeter set to 29.92 inches.

(b) *Liquid water content*

Tracings of the records produced by the liquid water content meter during the flights through the orographic cloud are shown in Figs. 7 to 14 inclusive. A scale showing the calibration of the instrument for a collection efficiency of 1.0 is superimposed on each record. Values of pressure altitude are usually given at each one-minute interval on the trace representing pressure altitude.

In the case of the measurements in seaward cumuli, tracings of the water content records have been provided only on the occasions on which simultaneous measurements are available of droplet spectra. These tracings are shown in Figs. 15, 16, and 17. The values of the maximum observed water content recorded as a function of height have been plotted in Fig. 4 for the cases in which representative measurements are available throughout the depth of the cloud.

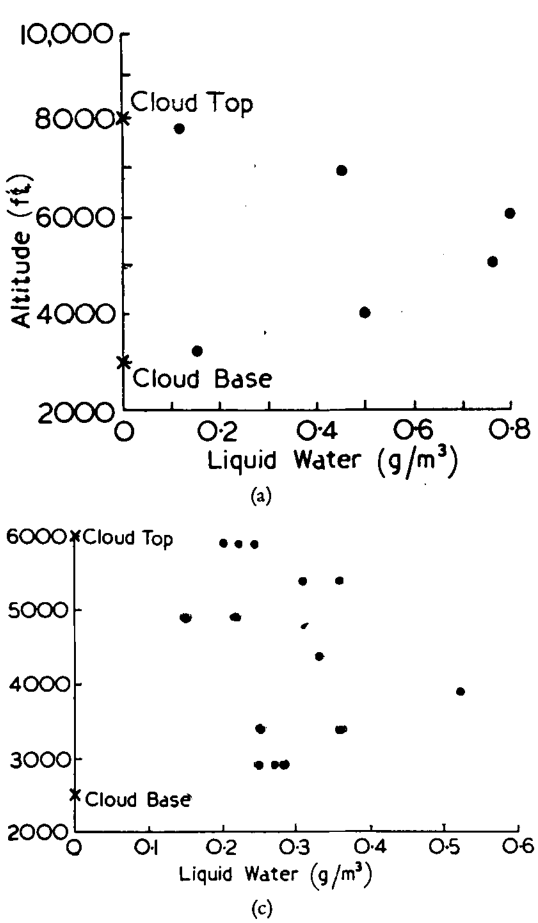


Fig. 4. Peak liquid water content during each passage through cloud plotted as a function of height for three typical seaward cumuli. (a) Observations made on 14 October 1954 between 1430 and 1500 hours. Initially there was no rain present in the cloud but on the last run through the cloud just above the base a small area of rain was encountered. (b) Measurements made on 23 October 1954. (See also Fig. 15.) (c) Observations made between 1430 and 1500 hours on 2 November 1954. No rain was observed in this cloud during the observation nor in any of the surrounding seaward clouds.

6. Discussion

(a) *Cloud droplet spectra*

The most striking feature of the spectra is the extraordinarily low droplet concentrations which occur in the orographic cloud on some occasions, in particular on the very rainy day December 2. As these low concentrations are not associated with low liquid water contents, it follows, as tables 1 to 6 show, that the average drop size was big on these occasions. November 6 differs quite noticeably from the other days in this respect. A slight tendency appears for the droplet concentrations to increase towards the coastal end of the orographic cloud. The seaward cumuli had rather larger concentrations. In this respect they resemble clouds of similar size observed off the east coast of Australia.

Some of these points are illustrated in Fig. 5, which shows histograms of the distribution of droplet concentration in steps of ten droplets per cc for each pass through the orographic cloud and for the seaward cloud on any one day.

These features of the droplet spectra can be related to the rate of cooling associated with the various clouds. The orographic cloud forms in air which is climbing up the volcano slopes with an average vertical speed of the order of 10 cm sec^{-1}—corresponding to a horizontal wind speed of 2 m sec^{-1}. At this low vertical speed it is not surprising therefore that its spectra typically show larger and fewer droplets than the seaward cumuli. It has been remarked earlier that the coastal part of the orographic cloud tended to be cumuliform, in contrast to the stratiform cloud towards the Saddle; this agrees with the slight tendency which appears for the droplet concentrations

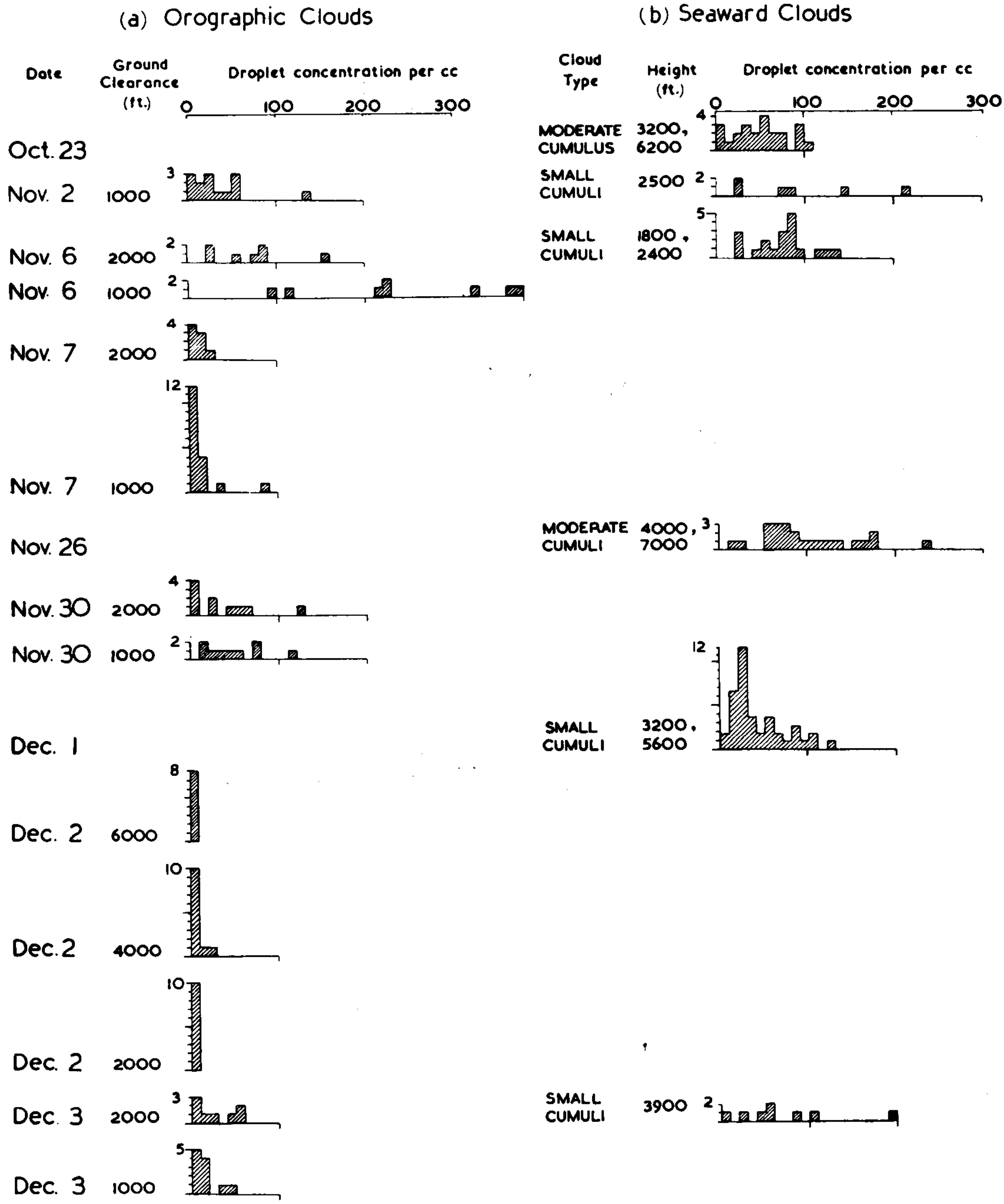


Fig. 5. Histograms of the droplet concentrations found in (a) orographic clouds, and (b) seaward clouds. Interval of concentration = 10 per cc. The vertical scale (number of occurrences) is given by the number entered at the upper left hand corner of each histogram. Under (b) seaward clouds, the column labelled "Height (ft)" indicates the limits between which observationse wer made.

to increase near the coast. On the exceptional day, November 6, when the orographic cloud had a micro-structure very similar to offshore cumulus, the liquid water content trace shows that the cloud was more cellular and presumably therefore more convective than usual.

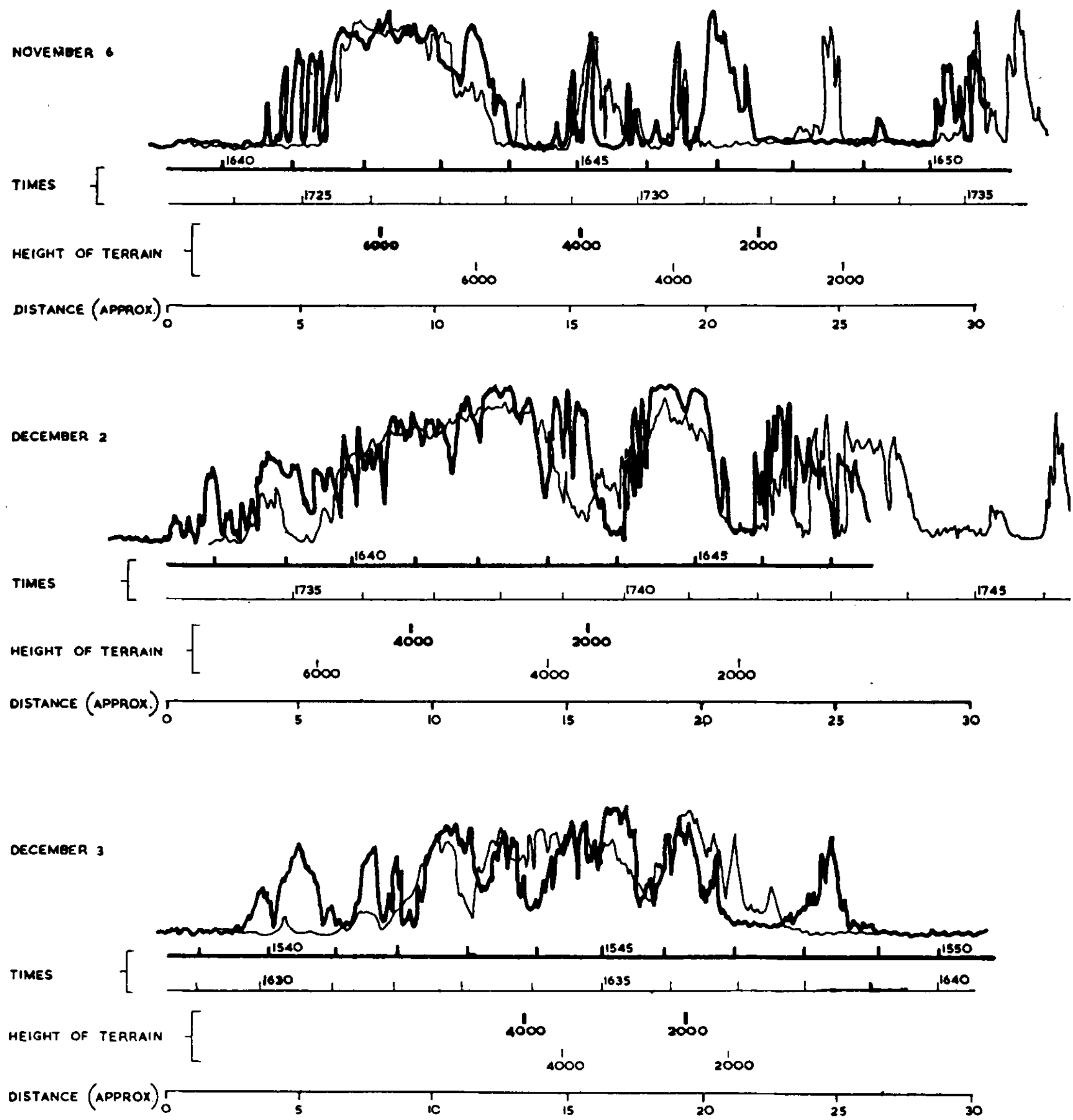


Fig. 6. Liquid water content traces on successive runs through the orographic cloud on each of three days. The first run is indicated by a heavy line and is superimposed on that for the succeeding run, indicated by a light line, in such a way that the best fit of the cellular structure is obtained. The time scales corresponding to the liquid water traces are given below them. The corresponding heights of the terrain beneath the aircraft are shown in the next two lines. The same convention of thick and thin lines is adhered to in both these cases. From the relative shift of the cloud cells and the time interval between runs the velocity of movement can be deduced.

The unusual micro-structure of the orographic cloud is no doubt related to the fact that although its depth is small, ranging from about 2,000 ft. near the Saddle to about 5,000 ft. on the coast on most occasions, it nevertheless produces significant amounts of rain. In contrast, the seaward cumuli did not seem to produce rain until they reached a depth of at least 6,000 ft. Many observations on non-freezing maritime cumuli off the east coast of Australia indicate that these clouds too in general need to be about 6,000 ft. deep in order to produce rain.

It will be seen from the tables that, even

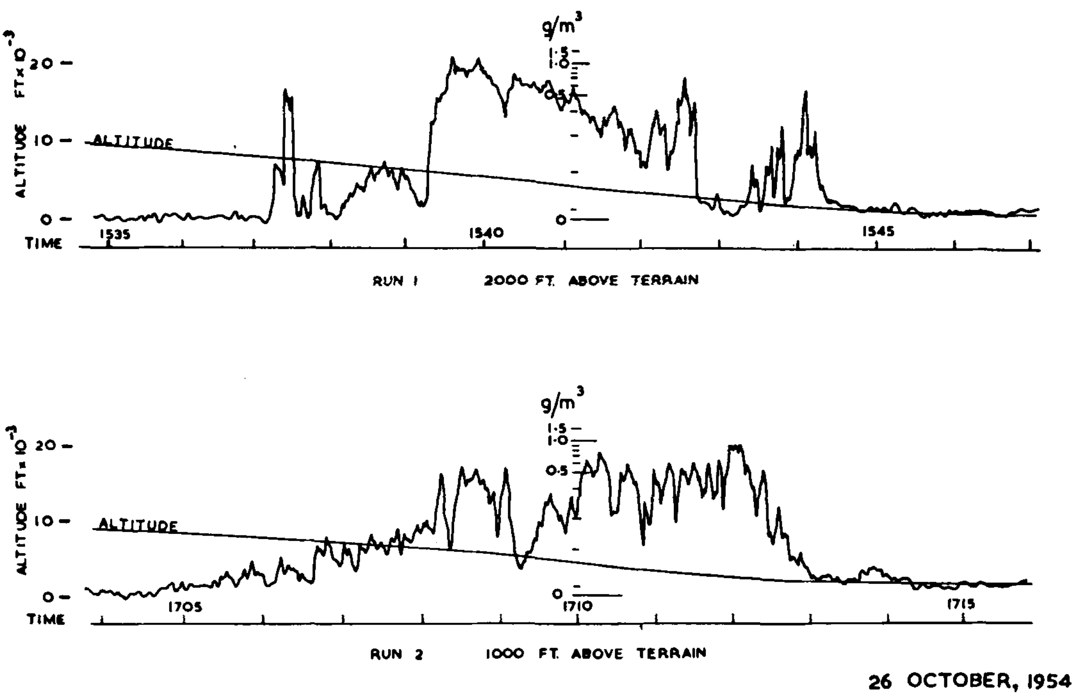


Fig. 7. Liquid water content traces through the orographic cloud at ground clearances of 2,000 and 1,000 ft on 26 October 1954. The smooth curve gives the aircraft altitude. By the time of the second run the cloud in the Saddle area had become much thinner and the clear lane greater in length. Droplet samples were not obtained on this flight.

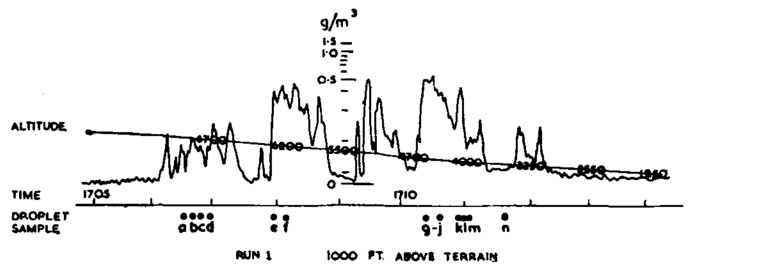


Fig. 8. Liquid water content trace through the orographic cloud at a ground clearance of 1,000 ft on 2 November 1954. The lettered dots refer to cloud droplet samples (see table 1). The figures on the altitude trace represent the aircraft altitude at one-minute intervals. Light rain began at sample j and continued down to just beyond cloud base at 2,500 ft.

when the average drop size is quite large, there are still small drops present. The orographic cloud is characterized by a very wide droplet spectrum; it contains in addition to the drop sizes which were found in the seaward cumuli, an extended range of much larger drops.

(b) *Liquid water content*

The most distinctive feature of the records is the indication of the cellular nature of the orographic cloud particularly towards its seaward edge. The water content in the orographic cloud seldom rose above 1 gm m^{-3} unless there was rain in the cloud. Thus on

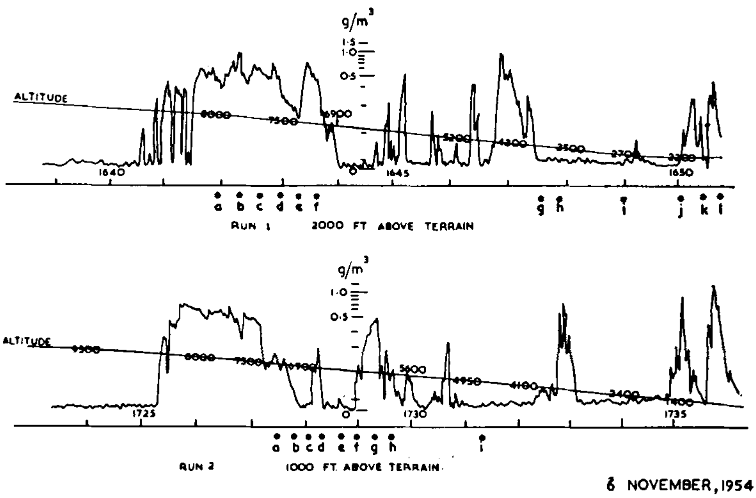


Fig. 9. Liquid water content traces through the orographic cloud at ground clearances of 2,000 and 1,000 ft on 6 November 1954. Top of cloud near the coast was bubbly with height variations of about 200 ft. There was a distinct trough in the cloud top 6 or 7 miles inland from Hilo running on a bearing 150°—330°. By the time the second crossing of the coast was made, about an hour later, the trough in the cloud tops had moved inland by 4 or 5 miles.

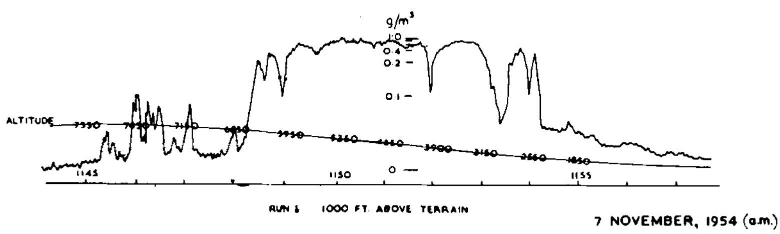


Fig. 10. Liquid water content trace through the orographic cloud at a ground clearance of 1,000 ft on the morning of 7 November 1954. The cloud tops were rather irregular in height and the orographic cloud in the Saddle area was very broken up with the ground frequently visible through it. West of the Saddle area cloud was just commencing to build. Droplet samples were not obtained on this flight.

December 2, when heavy rain was falling, the water content rose to a maximum of 4 gm m^{-3}. This value of course includes the rainwater content, or that part of it contained in the smaller drop size ranges, since some of the larger drops may be lost due to splashing. There does not appear to be any simple relationship between water content and either ground clearance or altitude.

An attempt was made to trace the movement of individual cloud cells between successive runs through the cloud. This met with some success, particularly in the case of the flights on December 2. Fig. 6 shows the result of superimposing the water content records for successive runs on each of three days after shifting the traces to obtain the best fit from one curve to the next. From the known time interval between runs, and the observed shift, rate of upslope drift of the cloud cells can be deduced. The values obtained were 4.5, 5 and 2.5 knots for November 6, December 2 and December 3 respectively. The corresponding Hilo rawindsonde velocities were 5—6, 5—10 and 3—5 knots.

The values of liquid water found in the seaward cumuli were similar to those experienced in cumuli observed near the eastern

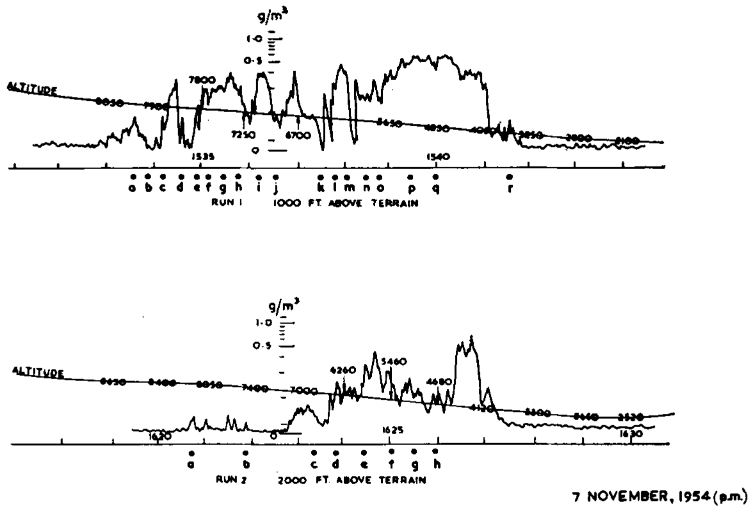


Fig. 11. Liquid water content traces through the orographic cloud at ground clearances of 1,000 ft and 2,000 ft on the afternoon of 7 November 1954. The orographic cloud was quite flat-topped in appearance except near the Saddle where it was cumuliform, with the ground visible through clear patches. A clear lane 2 miles wide extended right across between the two mountain peaks. (See Photo 2.) Light rain was observed in the cloud all the way down at 1,000 ft ground clearance, heaviest at the coastal end of the run.

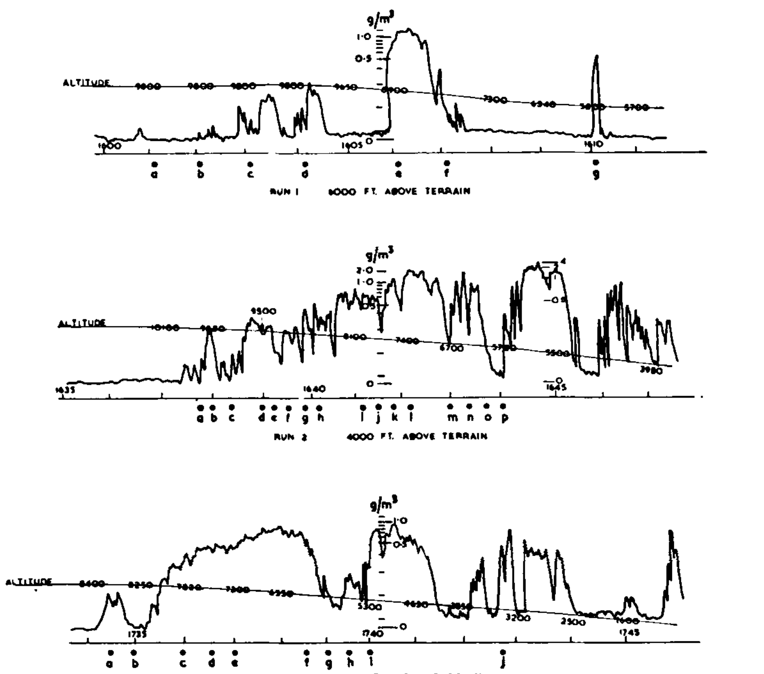


Fig. 12. Liquid water content traces through the orographic cloud at ground clearances of 6,000, 4,000 and 2,000 ft on 2 December 1954. The orographic cloud was deeper than usual with its tops rising to 11,000 ft. The cloud edge in the Saddle was seen to be raining lightly and rain was encountered on all runs. On the 4,000-ft run the rain was heavy between 1644 ½ hours and 1645 hours.

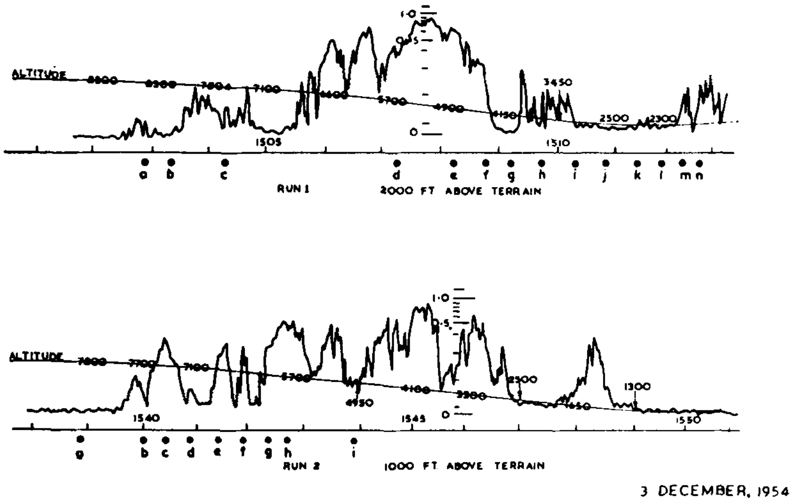


Fig. 13. Liquid water content traces through the orographic cloud at ground clearances of 2,000 and 1,000 ft on 3 December 1954. The cloud edge in the Saddle was not raining and very little rain was encountered throughout the cloud.

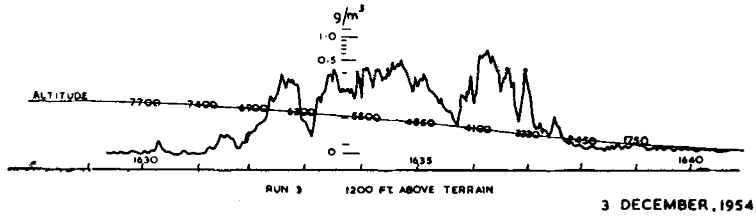


Fig. 14. Liquid water content trace for a run through the orographic cloud at a ground clearance of 1,200 ft on 3 December 1954. Droplet samples were not obtained on this run.

Australian coast. The variation of water content with height, and the ratio between the measured and adiabatic values of liquid water content, were also similar.

If the liquid water content values deduced from the drop spectra are compared with corresponding values on the water content meter records it will be seen that there is only general agreement. There is certainly no consistent difference. Thus it appears that there are fluctuations in the cloud in most places which are too rapid for the water content meter to follow. MALKUS et al. (1948) found evidence of such very rapid changes in cloud. Another factor is that the spectra have been limited to the region $d < 200\,\mu$, which is the conventional boundary between cloud drops and drizzle. On a number of exposed rods, traces were found corresponding to larger drops, but none in numbers sufficient to be statistically representative. Nevertheless, drops of these very large sizes seemed at times to contribute quite substantially to the total liquid water.

7. Conclusion

The seaward cumuli were similar in liquid water content, spatial distribution of water, micro-structure and degree of collodial instability to non-freezing maritime cumuli observed off the east coast of Australia.

The orographic cloud averaged 4,000 to 5,000 ft. in depth at the coast, decreasing to about 2,000 ft. at the Saddle on most occasions. The upper surface of the cloud rather resembled that of strato-cumulus. Observed from within,

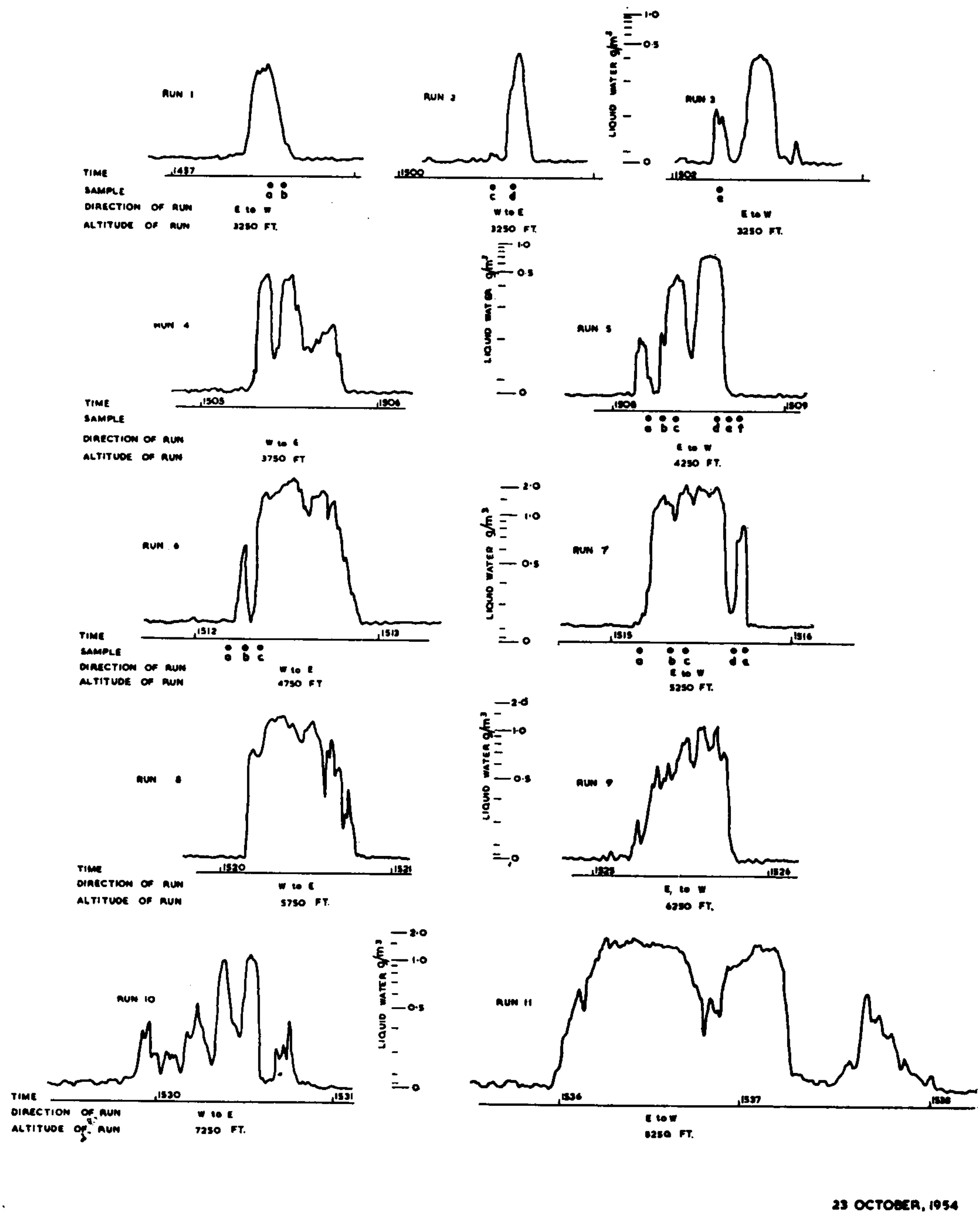


Fig. 15. Liquid water content traces through an isolated growing cumulus 10 miles off Cape Kumukahi on 23 October 1954. The passes were made alternately east to west and west to east. The cloud was elongated north and south; the southern end was raining from the beginning, but the northern end, where the observations were taken, was not at first. Within 10 minutes however rain was encountered over a portion of each pass. Cloud base was at 2,200 ft and the top, which was enveloped in a stratus canopy, was estimated to be at 9,500 ft at the completion of the operation. (See also Fig. 4 (b),)

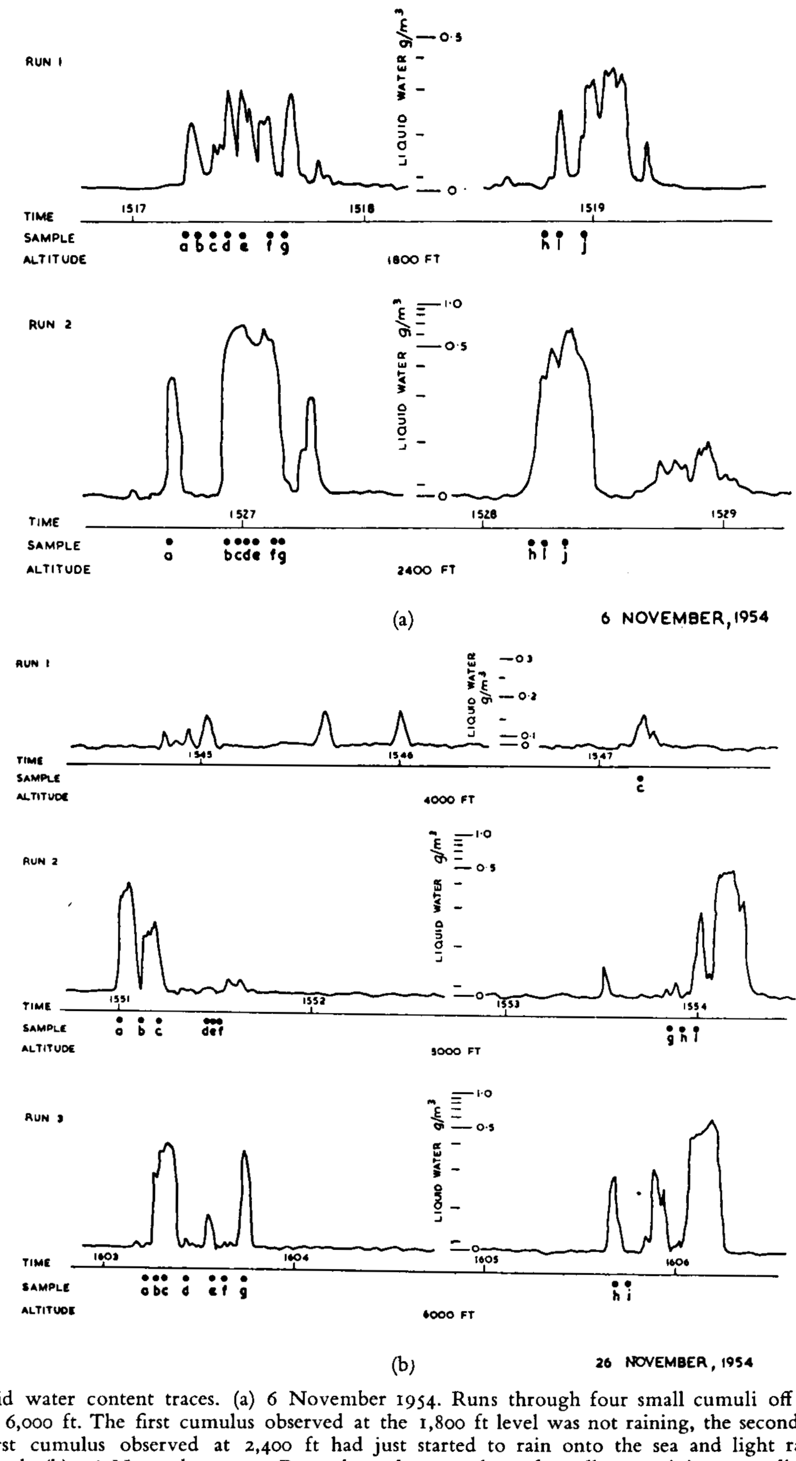


Fig. 16. Liquid water content traces. (a) 6 November 1954. Runs through four small cumuli off Hilo, bases 80 ft, tops about 6,000 ft. The first cumulus observed at the 1,800 ft level was not raining, the second had light rain in it; the first cumulus observed at 2,400 ft had just started to rain onto the sea and light rain was falling from the second. (b) 26 November 1954. Runs through a number of small non-raining cumuli off Hilo; bases 3,600 ft, tops usually 7,500 ft but occasionally to 9,000 ft. No rain was experienced in the clouds sampled and only a few of the bigger clouds over the sea were raining.

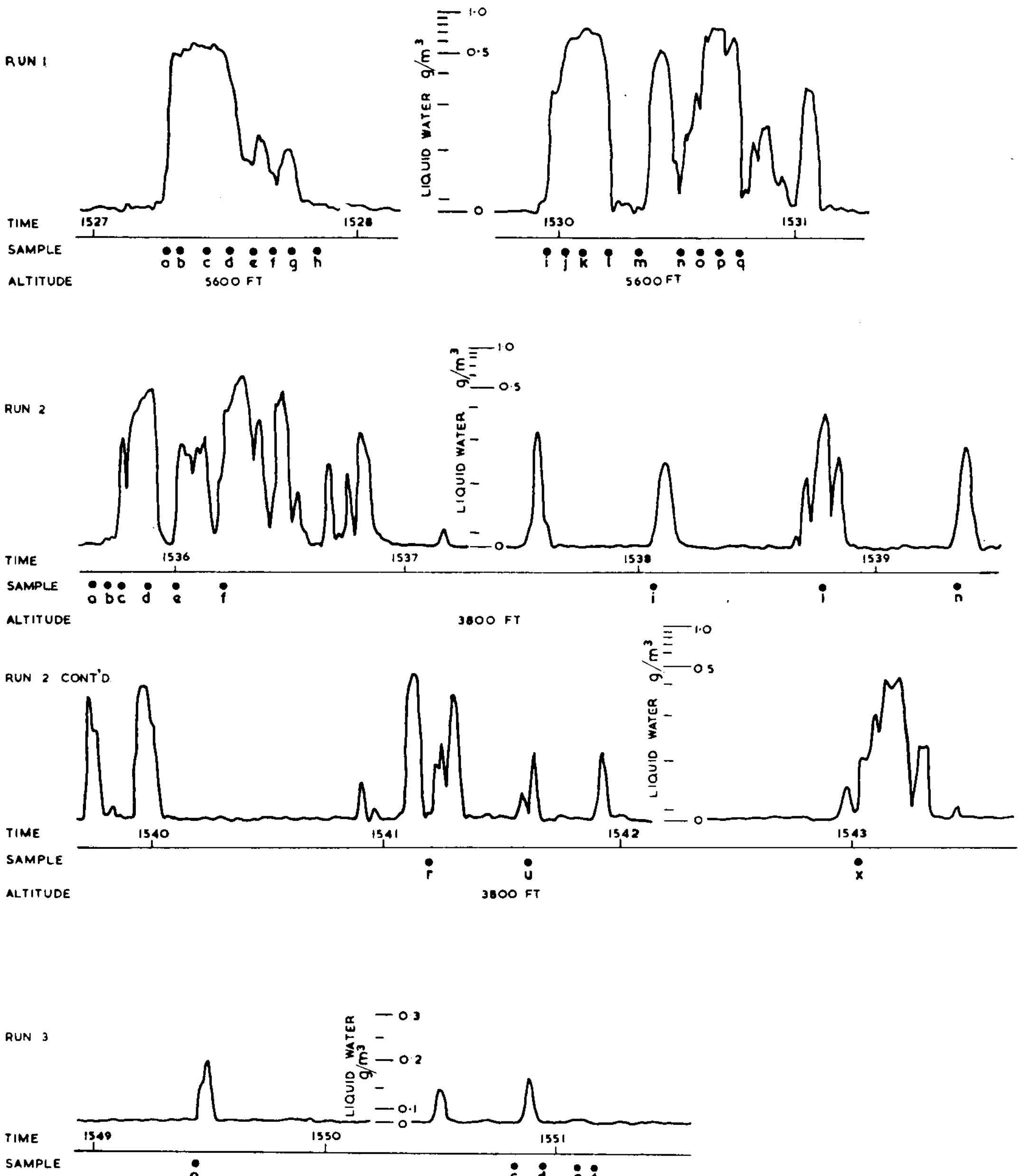


Fig. 17. Liquid water content traces for passes through a number of small cumuli off Hilo on 1 December 1954. Bases 2,500 ft, tops 6,500 ft except for the last run at 3,200 ft when the top was at 3,500 ft. Rain was encountered for brief periods at 1530 ½ hours and at 1536 hours.

it consisted of two distinct zones; on the upper slopes it was stratiform; near the coast it showed a cellular, cumuliform structure. The transition was fairly sharp, and usually occurred a little more than half way up the slope from Hilo to the Saddle.

The total liquid water content (cloud and rain) was nearly always well below 1 gm m^{-3}, except in heavy rain. The cellular structure shown in the liquid water content traces sometimes persisted recognizably for periods of about an hour, and when this happened, the speed of upslope movement of the cloud masses derived from the traces obtained on successive runs agreed reasonably well with the upper wind observations.

The micro-structure of the orographic cloud showed fewer and larger drops than were found in seaward cumuli; this can be explained in terms of the slow lifting of the air mass up the volcano slopes, and in turn it seems likely that it explains the remarkably fine but dense rain which falls from this cloud, and the ability of the orographic cloud to produce rain, although it is relatively shallow.

8. Acknowledgements

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