Trade Wind Cloud Measurements Windward of the Island of Hawaii

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1. Introduction

Aircraft observations upwind of the Island of Hawaii were made to obtain detailed soundings of air temperature and water vapor over the sea upwind of the Hilo area. It was desirable to know how representative a single sounding was for a short time period during "budget" days. Measurements were made of temperature and water vapor content in clear air and liquid water content in clouds which subsequently moved over the raingage network on the windward slopes of Mauna Loa and Mauna Kea.

A single engine Howard aircraft (Fig. 1) was used for these flights. Continuous re-

Fig. 1. Howard aircraft used to obtain observations windward of the Island of Hawaii. The liquid water content sensing unit is beneath the port wing. The vortex thermometer under the starboard wing was replaced by the psychrometer unit during "Project Shower".

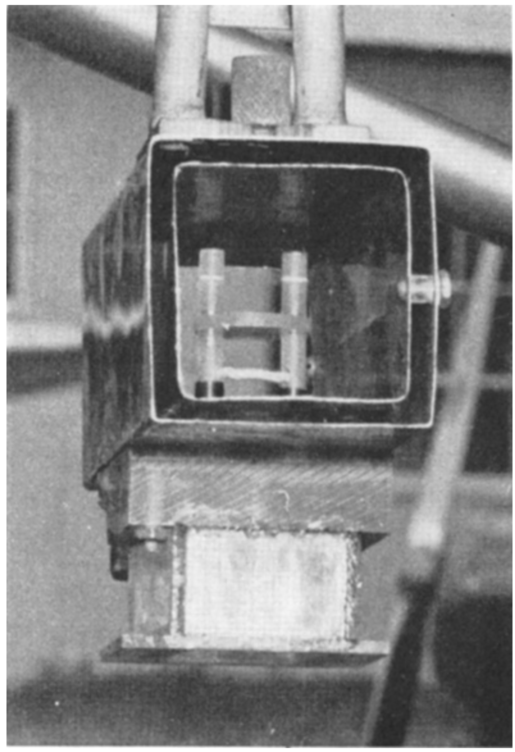

Fig. 2. Psychrometer sensing unit used for measurements of dry and wet bulb temperatures. The double radiation shield surrounds the thermocouples which are mounted on a pedestal attached to the plastic water reservoir beneath the shield.

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[2] Present affiliation: U.S. Weather Bureau, Washington, DC.

cordings were made of dry and wet bulb temperatures and liquid water content. Aircraft instruments were photographed once a second. Visual and photographic observations of clouds and precipitation were taken to assist in the interpretation of the recorded data.

Temperature and water vapor measurements.— Dry and wet bulb temperature measurements were made using copper-constantan thermocouples fabricated from number 30 Brown and Sharpe gage wire, mounted in a radiation shield located beneath the starboard wing of the aircraft (Fig. 2). The thermocouples were connected alternately each second to the input of a high speed recording potentiometer with a range of — 0.15 to + 1.50 millivolts. The record thus produced (Fig. 3) is a trace where the width indicates the bulb depression and right hand edge the air temperature. One-quarter recorder division (110 recorder divisions for full scale pen travel) approximately equals 0.1° C. The recorder system is still more sensitive so that indicated temperatures can be read to 0.1° C.

The indicated temperature readings are corrected for adiabatic and frictional heating as described by MIDDLETON and SPILHAUS (1953). Radiation errors are negligible as sensing elements are small, and there was a double, concentric radiation shield and high ventilation rate. The overall accuracy of the psychrometer was considered to be better than ±0.3° C with the relative accuracy ±0.1° C. The error in absolute measurement is primarily due to the inaccuracy in determining the correction for dynamic heating.

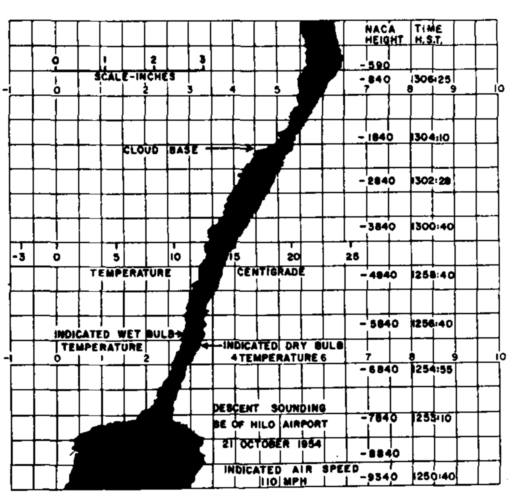

Fig. 3. Psychrometer recorder record indicating a descent sounding made at 1250 to 1306 HST 21 October 1954 southeast of Hilo Airport. The chart speed is approximately one division ($^1/_2$ in) per minute.

All height data are expressed as pressure altitude, based on the U.S. (or National Advisory Committee for Aeronautics) Standard Atmosphere.[1] These values can be converted directly into pressure using the conversion tables prepared by BELLAMY (1945) and the pressure-height data from the Hilo Weather Bureau radiosonde observations.

The water vapor content of the air is in terms of mixing ratio, grams of water per kilogram of dry air. Mixing ratio was evaluated using a slide rule with NACA height, wet bulb temperature, and wet bulb depression as arguments. The accuracy of the mixing ratio values is ±0.2 gm/kg.

Liquid water content measurements. — The sensing unit for the measurement of cloud liquid water content was of the paper tape type designed by WARNER and NEWNHAM (1952) and kindly furnished by Dr. E. G. Bowen of the Commonwealth Scientific and Industrial Research Organization of Australia. Warner's original calibration of the instrument was rechecked during "Project Shower". This check was within 5 per cent of the earlier calibration made in Australia. The accuracy of the method is considered by Warner and Newnham to be about 25 per cent.

Aircraft instruments, the readings of which are needed to evaluate the meteorological data, were mounted in a photo box where a modified 16 mm movie camera photographed them once a second. Marker pens on each of the recorders and a light on the photo box instrument panel were connected to a push-button switch. This permitted the simultaneous marking of all the records for time checks and synchronization of data.

2. Observational Data

Soundings.—On nine days during the project, detailed vertical soundings of temperature and water vapor content were taken over the sea upwind of Hilo. These soundings are

[1] The heights are thus as indicated by an aircraft altimeter with altimeter setting at 29.92 in. This parameter will be referred to as NACA height.

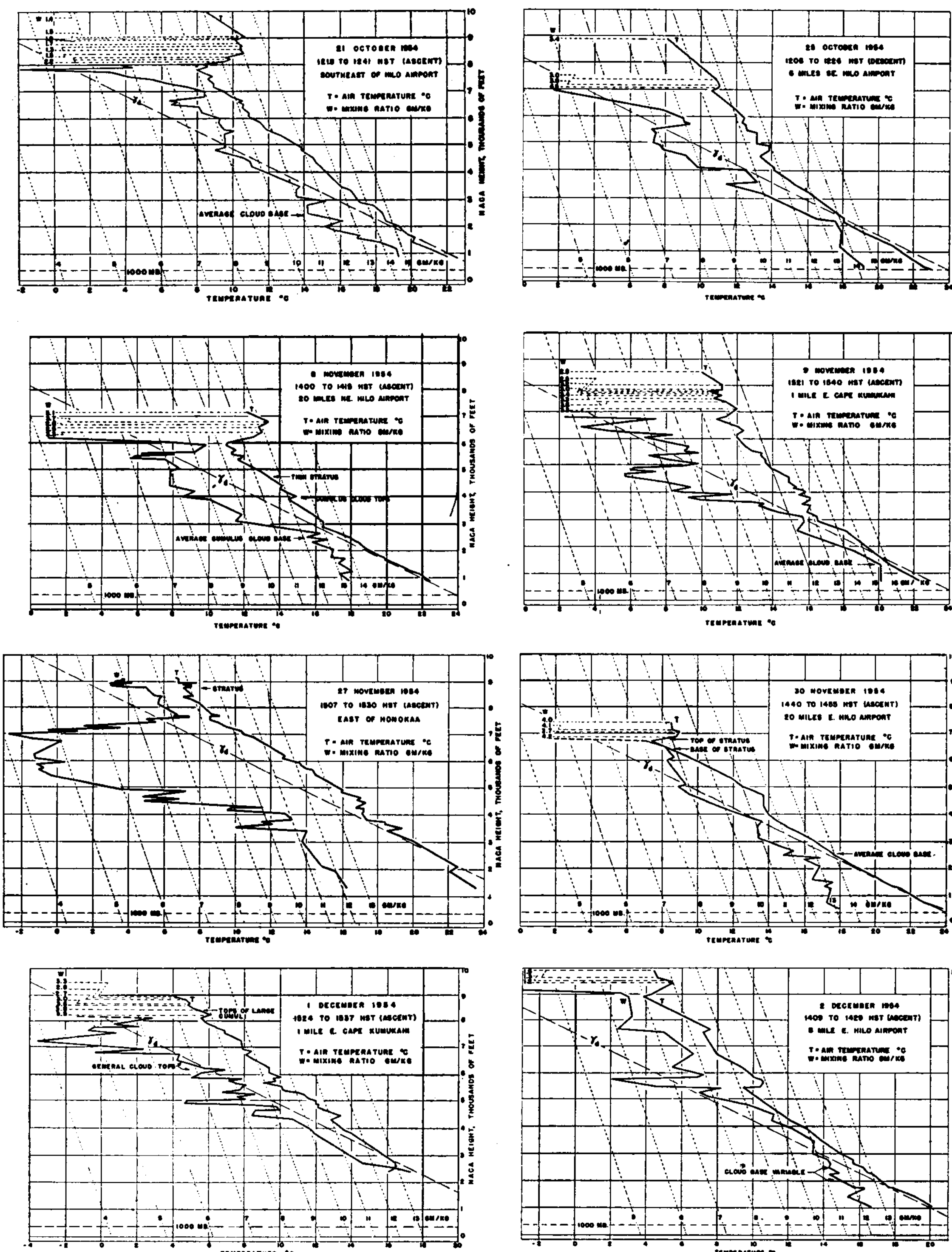
21 OCTOBER 1954
1218 TO 1241 HST (ASCENT)
SOUTHEAST OF HILO AIRPORT
T = AIR TEMPERATURE °C
W = MIXING RATIO GM/KG
AVERAGE CLOUD BASE
1000 MB.
TEMPERATURE °C
NACA HEIGHT, THOUSANDS OF FEET
28 OCTOBER 1954
1206 TO 1226 HST (DESCENT)
6 MILES SE. HILO AIRPORT
8 NOVEMBER 1954
1400 TO 1419 HST (ASCENT)
20 MILES NE. HILO AIRPORT
THIN STRATUS
CUMULUS CLOUD TOPS
AVERAGE CUMULUS CLOUD BASE
9 NOVEMBER 1954
1521 TO 1540 HST (ASCENT)
1 MILE E. CAPE KUMUKAHI
27 NOVEMBER 1954
1507 TO 1530 HST (ASCENT)
EAST OF HONOKAA
STRATUS
30 NOVEMBER 1954
1440 TO 1455 HST (ASCENT)
20 MILES E. HILO AIRPORT
TOP OF STRATUS
BASE OF STRATUS
1 DECEMBER 1954
1524 TO 1537 HST (ASCENT)
1 MILE E. CAPE KUMUKAHI
TOPS OF LARGE CUMULI
GENERAL CLOUD TOPS
2 DECEMBER 1954
1409 TO 1429 HST (ASCENT)
5 MILE E. HILO AIRPORT
CLOUD BASE VARIABLE

Fig. 4 a—h.

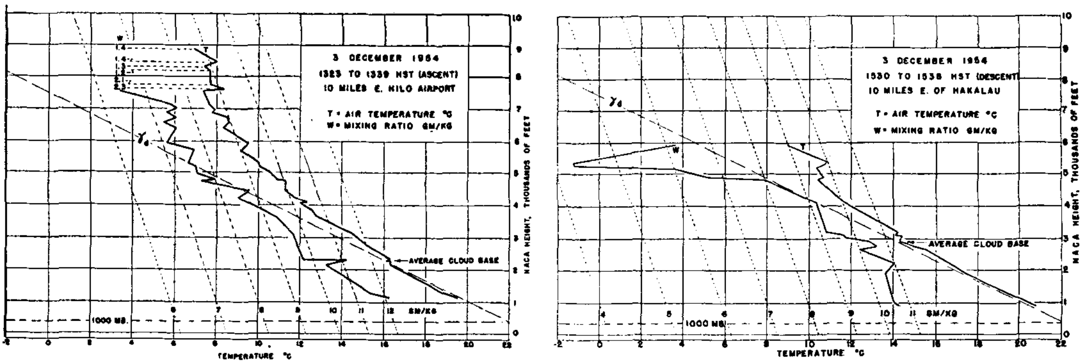

Fig. 4 i—j.

Fig. 4 a—j. Aircraft soundings taken upwind of the Hilo coast during the project. The dry adiabatic lapse rate is indicated by the line γ_d. Low values of mixing ratio are indicated numerically rather than graphically and connected to the corresponding points on the temperature curve by dashed lines.

presented in Fig. 4 a—j. For detailed study, these data are also presented in tabular form in table 1.

The data have not been fully analysed or correlated with observations made by other participants in "Project Shower". However, there are certain features which may be noteworthy to those using these data.

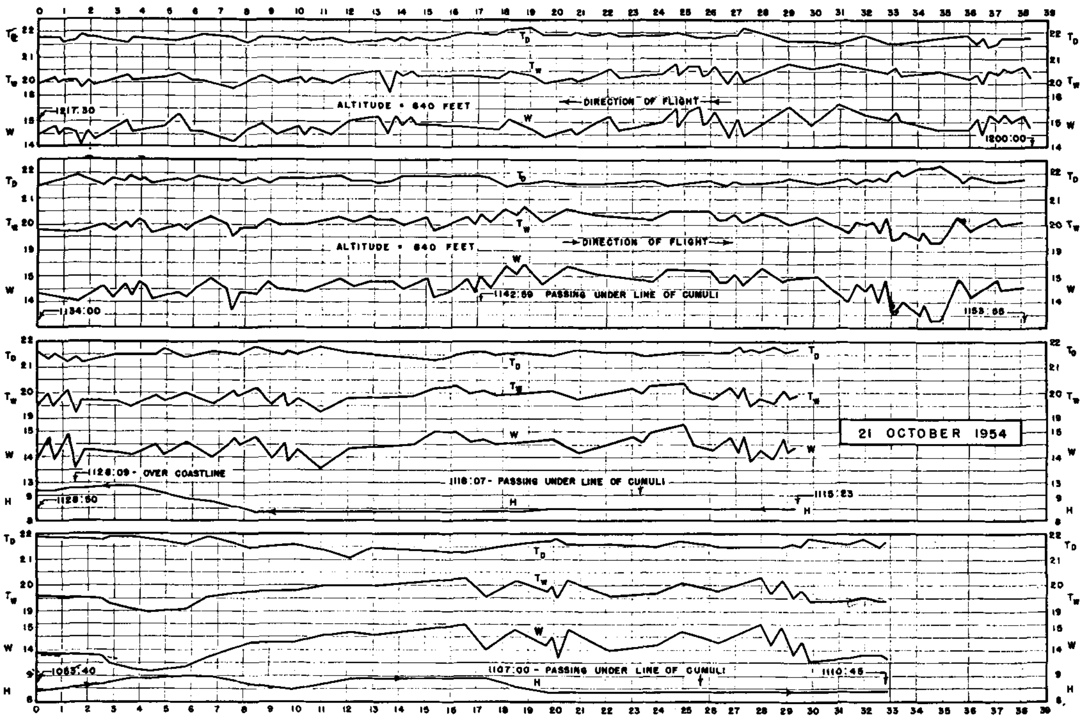

Fig. 5. Observations of dry bulb (T_D) and wet bulb (T_W) temperatures, in degrees Centigrade, mixing ratio (W) in grams per kilogram, and NACA height of observation (H) in hundreds of feet obtained on 21 October 1954. Four traverses approximately parallel with the trade wind flow were made in the sub-cloud layer upwind of the Island of Hawaii. Times are given in hours, minutes, and seconds HST.

Table 1. Aircraft sounding data obtained over the sea east of the Island of Hawaii.

Dry bulb (T_D) and wet bulp (T_W) temperatures are in degrees centigrade, mixing ratio (W) in grams per kilogram, and NACA height (H) in feet. Date, 1954, time, and location are indicated in the heading for each sounding.

21 Oct, 1218-1241 HST
SE of Hilo Airport

H	T_D	T_W	W
840	22.1	20.2	14.6
1140	21.0	19.8	14.7
1410	20.1	18.8	13.9
1540	20.2	17.9	12.8
1670	19.8	17.9	13.0
1840	19.5	17.0	12.0
1990	19.3	16.6	11.7
2180	18.6	17.0	12.5
2490	18.4	15.8	11.2
2790	17.8	15.5	11.3
2920	17.1	15.9	12.1
3090	16.8	14.8	11.0
3340	16.6	14.8	11.1
3440	16.1	14.7	11.3
4210	14.9	12.6	9.7
4340	14.7	12.5	9.7
4520	14.5	12.1	9.5
4800	13.8	11.0	8.6
4900	13.8	11.2	9.0
5380	12.7	10.8	9.1
5510	12.2	10.9	9.5
5570	11.9	10.5	9.2
5840	11.5	10.2	9.1
6010	11.0	10.0	9.2
6060	10.9	9.5	9.0
6230	10.9	9.4	8.6
6400	10.5	9.1	8.6
6480	10.6	8.2	7.7
6610	10.3	8.3	7.9
6660	10.5	8.2	7.7
6790	9.9	9.0	8.9
7000	9.4	8.9	9.0
7170	8.9	8.1	8.4
7300	8.9	7.4	7.8
7440	8.6	6.7	7.4
7570	8.8	6.2	6.8
7710	8.3	5.5	6.4
7790	8.0	4.1	5.3
7880	8.4	3.3	4.5
7920	8.6	6.2	7.0
8000	8.3	5.8	6.7
8090	9.6	1.5	2.5
8200	9.9	1.3	2.2
8250	9.6	1.1	2.2
8420	10.6	0.7	1.5
8610	10.4	0.3	1.3
8710	10.5	0.4	1.3
8790	10.3	0.7	1.7
8960	10.2	0.5	1.9
9030	10.7	0.5	1.5
9990	8.5	−0.9	1.4

25 Oct, 1208-1226 HST
6 miles SE Hilo Airport

H	T_D	T_W	W
8880	8.1	1.6	3.4
7340	10.9	2.9	3.0
7120	11.1	4.1	3.8
7060	11.0	5.3	4.5
6990	10.6	5.6	5.3
6270	12.0	9.5	8.4
5940	12.4	10.4	9.0
5810	12.3	10.4	9.0
5670	12.5	10.7	9.2
5540	12.6	9.5	7.8
5390	13.2	9.8	7.9
5010	13.2	9.8	7.7
4880	13.8	10.2	7.9
4720	13.8	10.4	8.0
4560	13.3	10.8	8.6
4110	14.2	11.6	8.9
4060	14.2	13.2	10.6
3580	15.1	13.9	10.9
3510	15.3	13.0	9.7
3220	16.0	14.5	11.0
2240	18.1	17.0	12.8
2130	18.1	17.8	13.7
1760	19.2	18.3	13.8
1240	20.8	18.8	13.5
520	22.5	20.3	14.4
380	23.1	20.4	14.3

8 Nov, 1400-1415 HST
20 miles NE Hilo Airport

H	T_D	T_W	W
890	22.5	19.4	13.4
1170	21.8	18.7	13.0
1250	21.4	19.1	13.7
1570	20.6	18.4	13.2
1710	20.0	18.4	13.6
1740	19.9	17.8	12.9
2060	18.9	17.7	13.2
2330	18.4	16.7	12.3
2390	18.2	17.2	13.0
2490	17.9	16.4	12.2
2640	17.3	16.6	12.8
2890	16.5	14.9	11.2
3110	16.4	13.5	9.6
3370	15.8	13.4	9.9
3890	14.5	11.7	8.9
4000	14.9	11.2	8.1
4140	14.3	11.2	8.5
4290	14.0	10.7	8.1
4410	14.2	10.4	7.8
4950	12.8	9.9	8.0
5040	12.5	10.1	8.3
5390	11.7	9.3	7.9
5430	11.8	8.4	7.0
5500	11.9	8.5	7.1
5550	11.4	9.5	8.3
5600	11.3	8.4	7.3
5640	11.3	10.1	9.0
5740	11.5	10.3	9.2
5940	11.0	9.8	9.5
6030	11.1	9.2	8.3
6220	12.5	6.5	5.2
6420	13.0	4.6	3.3
6630	12.8	3.5	2.5
6710	13.2	4.0	2.8
6810	13.3	5.0	3.7
7140	12.1	5.9	5.1

9 Nov, 1521-1540 HST
1 mile E Cape Kumukahi

H	T_D	T_W	W
720	22.2	20.9	15.4
1370	20.6	20.3	15.7
1820	19.7	19.1	14.6
2590	18.1	16.3	12.1
2950	16.6	16.2	12.6
3090	16.5	16.0	12.6
3330	15.9	14.9	11.6
3500	16.1	14.3	10.9
3560	15.7	14.4	11.2
3660	15.9	13.9	10.6
3710	16.1	12.4	8.8
3820	16.1	12.0	8.4
3920	15.4	13.1	10.0
3960	15.8	11.8	8.4
4050	15.7	11.3	8.0
4140	15.2	11.7	8.6
4210	15.3	11.2	8.1
4380	14.9	10.9	7.9
4610	14.9	9.7	6.8
4670	14.7	9.6	6.8
4750	14.3	10.3	7.7
4860	14.0	9.5	7.0
4940	13.9	9.5	7.1
4980	13.8	10.9	8.6
5080	13.6	11.3	9.2
5220	13.6	10.3	8.2
5370	13.3	9.5	7.6
5470	13.4	11.2	9.3
5560	12.8	10.5	8.8
5640	12.5	10.6	9.1
6070	12.0	8.9	7.7
6170	12.0	9.8	8.6
6300	12.4	8.1	6.8
6450	12.0	7.2	6.1
6750	10.8	8.8	8.3
6860	11.4	6.0	5.8
7100	12.0	3.9	3.3
7400	11.3	4.1	3.8
7520	10.7	3.8	3.8
7610	11.1	3.3	3.3
7690	10.7	3.2	3.4
7740	11.0	3.2	3.0
7780	10.4	3.1	3.2
7840	11.2	2.6	2.5
8020	11.2	2.3	2.5
8520	10.0	1.6	2.5

27 Nov, 1507-1530 HST
East of Honokaa

H	T_D	T_W	W
1320	23.6	18.6	12.2
1950	22.1	17.8	12.0
2120	22.5	17.4	11.5
3070	19.9	15.9	11.1
3400	18.5	15.6	11.4
3530	19.4	13.6	8.8
3640	18.4	14.5	10.2
3720	18.4	14.1	9.8
3820	17.4	14.7	11.0
4040	17.1	14.4	10.8
4150	17.2	12.5	8.7
4220	17.2	13.1	9.4
4250	16.7	13.5	10.0
4480	17.3	10.2	6.4
4550	16.8	10.9	7.3
4630	17.0	10.1	6.4
4830	15.9	10.7	7.6
4900	16.0	9.1	5.9
5470	14.6	7.0	4.6
5670	14.3	6.6	4.4
5710	14.0	6.6	4.5
5860	13.7	6.3	4.4
5930	13.6	6.7	4.9
6120	12.7	5.8	4.4
6210	12.8	5.9	4.4
6760	11.4	5.7	5.0
6870	11.1	4.9	4.5
6980	10.5	4.7	4.1
7090	10.3	5.5	5.4
7110	10.2	4.8	4.8
7230	9.6	6.2	6.4
7320	9.4	5.3	5.6
7440	9.0	6.9	7.4
7570	8.6	6.5	7.2
7620	8.6	7.8	8.5
7670	9.2	7.7	8.1
7720	8.7	7.5	8.2
8140	8.0	6.6	7.7
8330	7.5	6.5	7.8
8400	7.1	6.4	7.9
8440	7.6	6.4	7.7
8740	7.1	5.8	7.5
8800	7.6	5.4	6.9
8870	7.5	5.1	6.6
8890	7.1	5.4	6.9
8910	7.8	5.2	6.6
8970	6.8	5.4	7.2
8990	6.8	4.8	6.7
9020	6.8	5.1	7.0
9070	6.7	5.0	6.9

30 Nov, 1440-1455 HST
20 miles E Hilo Airport

H	T_D	T_W	W
500	23,8	19.8	13.2
750	22.7	19.0	12.7
1230	21.4	18.7	13.1
1350	20.9	18.3	12.9
1510	20.5	18.5	13.4
1600	20.2	17.7	12.5
2110	18.7	17.4	13.0
2340	18.2	16.7	12.4
2370	17.9	17.1	13.2

2500	17.7	15.8	11.6
2620	17.4	16.1	12.1
3120	16.3	14.5	10.9
3550	15.0	14.0	11.0
3720	14.5	14.0	11.3
3940	14.1	13.3	10.7
4220	13.7	12.2	9.8
4720	13.7	11.2	8.9
5000	12.6	10.4	8.6
5080	12.3	10.6	8.9
5300	12.0	10.3	8.8
6000	9.9	8.9	8.5
6140	9.5	8.9	8.7
6500	8.2	8.2	8.6
6760	7.4	7.3	8.1
6910	8.8	3.5	4.2
7060	9.0	3.0	3.7
7130	8.6	3.2	4.1
7420	8.5	3.0	4.0

1 Dec, 1524-1537 HST
1 mile E Cape Kumukahi

H	T_D	T_W	W
2400	17.3	16.5	12.5
2500	16.5	16.6	13.0
2700	16.5	15.4	11.7
3800	14.1	12.5	10.2
3940	13.6	12.6	10.1
4290	12.8	11.5	9.5
4450	13.4	10.4	8.2
4610	12.7	10.3	8.3
4660	12.4	11.0	9.2
4766	12.2	10.9	9.2
4840	12.2	10.0	8.3
4900	12.0	8.0	6.4
4980	12.0	8.1	6.5
5080	11.7	9.7	8.2
5150	11.5	9.2	7.9
5220	11.4	9.8	8.6
5300	11.0	8.6	7.5
5360	10.3	8.7	7.8
5410	10.2	9.3	8.6
5540	10.1	8.5	7.8
5580	10.0	8.9	8.3
5650	9.1	8.3	8.1
5710	9.8	8.3	7.8
5830	9.6	8.3	7.9
5890	10.1	7.3	6.8
6090	9.3	7.2	7.1
6150	9.3	7.9	7.8
6270	9.3	7.3	7.2
6570	8.7	6.3	6.6
6760	8.1	6.1	6.7
6850	8.4	4.1	4.8
6920	7.9	4.9	5.8
7270	7.8	2.6	3.9
7520	6.9	3.9	5.4
7610	6.9	3.2	4.8
7710	6.5	3.2	5.0
7780	6.4	4.1	5.9
7900	5.9	3.3	5.4
8110	5.5	4.1	6.3
8230	6.1	1.0	3.5
8450	5.2	0.9	3.8
8600	4.8	0.4	3.6
8640	5.0	−0.3	3.0
8810	4.7	−0.8	2.7
8900	4.3	−1.0	2.8
8960	4.0	−0.5	3.3

2 Dec, 1409-1429 HST
8 miles E Hilo Airport

H	T_D	T_W	W
1040	20.1	17.8	12.4
1170	19.8	17.5	12.2
1460	19.1	16.7	11.6
1780	17.9	16.8	12.4
1790	17.6	16.4	12.0
2260	16.7	15.3	11.2
2300	16.4	15.6	11.7
2530	16.2	15.1	11.3
2640	15.6	14.9	11.4
2790	15.6	14.8	11.4
3030	14.9	14.0	10.8
3500	13.8	13.7	11.1
3670	13.7	13.1	10.5
3920	13.1	12.7	10.4
4030	12.8	12.0	9.9
4210	12.2	11.6	9.7
4410	11.7	11.4	9.8
4800	10.8	10.3	9.1
5100	10.2	8.6	7.8
5230	9.9	8.3	7.6
5430	9.4	8.8	8.3
5480	10.4	7.3	6.5
5670	10.6	6.6	5.9
5730	10.5	6.2	5.5
5840	10.0	8.2	7.7
5920	9.9	8.4	7.9
6230	9.3	7.2	7.1
6720	8.0	7.2	7.8
7550	7.2	6.0	7.2
7660	7.6	4.8	6.0
8170	6.2	4.6	6.5
8920	3.8	3.4	6.6
9020	4.3	3.3	6.4
9440	5.4	−2.7	1.2
5910	5.3	−2.5	1.3
9630	4.6	−2.8	1.5
9920	4.4	−3.0	1.5

3 Dec, 1323-1339 HST
10 miles E Hilo Airport

H	T_D	T_W	W
1150	19.5	17.3	12.1
1300	18.8	16.7	11.6
2160	16.3	14.5	10.4
2240	16.3	15.0	11.1
2280	16.2	14.8	11.2
2320	16.3	13.8	9.7
2740	15.2	13.2	9.7
3100	14.6	12.9	9.7
3650	12.8	11.7	9.3
3850	12.6	11.2	9.0
4040	12.0	10.6	8.7
4080	12.3	10.6	8.6
4200	11.8	10.1	8.4
4440	11.3	10.3	8.8
4740	11.3	9.0	7.6
4780	10.9	9.3	8.0
5000	10.6	8.7	7.6
5180	10.1	8.4	7.6
5310	10.0	8.1	7.4
5740	9.2	8.0	7.7
5940	9.5	7.4	7.1
6400	8.3	7.1	7.4
6590	8.6	7.0	7.2
6750	8.5	7.1	7.5
6900	7.8	6.5	7.3
7010	7.9	6.9	7.6
7120	7.7	6.7	7.5
7560	7.3	5.2	6.4
7620	8.3	0.8	2.3
7750	7.7	0.2	2.1
8210	7.7	−1.0	1.2
8320	7.4	−1.1	1.3
8460	8.0	−0.9	1.4
8900	6.9	−1.4	1.4

3 Dec, 1530-1538 HST
10 miles E of Hakalau

H	T_D	T_W	W
5360	10.8	5.0	4.3
5280	10.7	5.1	4.3
5190	10.3	6.9	6.0
4910	10.7	7.7	6.6
4830	10.4	9.1	8.0
4130	11.6	10.7	9.2
3190	14.2	12.2	9.2
3090	14.1	12.7	9.7
3050	14.4	12.7	9.7
2900	14.3	13.5	10.4
2740	15.0	14.0	10.6
2650	15.5	13.5	10.0
2210	16.7	14.9	11.0
1900	17.4	15.1	10.6
1030	20.2	16.3	10.5
890	20.8	16.7	10.7

Temperature and water vapor fluctuations.— Since, on "budget" days, each observation would necessarily have to represent averages for a period of at least two hours, it was desired to examine the magnitude of the variations in temperature and water vapor content in the sub-cloud layer during trade wind conditions. Toward this end, on 21 October the Australian and Hawaiian planes each made four traverses roughly parallel with the wind at an altitude of about 900 ft. These traverses extended up to 38 mi upwind from the coast southeast of Hilo. The planes were to fly 5 mi apart at the same altitude. Unavoidable deviations did occur with the aircraft at times approaching to within one-half mi of each other.

The psychrometric data obtained by our plane are presented in Fig. 5. All traverses were made on a 070—250 deg bearing and the data are plotted against a common distance scale with the origin approximately at the coastline. Navigation was not precise enough to permit a direct comparison of a point on one traverse with that on another at the same indicated distance from the origin. The error in distance is estimated to be about ± 1 mi.

The overall range in air temperature throughout the four traverses was 1.2° C while the maximum change on each traverse varied from 0.6 to 0.8° C. The overall range of wet bulb temperature was 1.8° C, and of mixing ratio 2.5 gm/kg. The larger variation in water vapor content is to be expected as the sounding

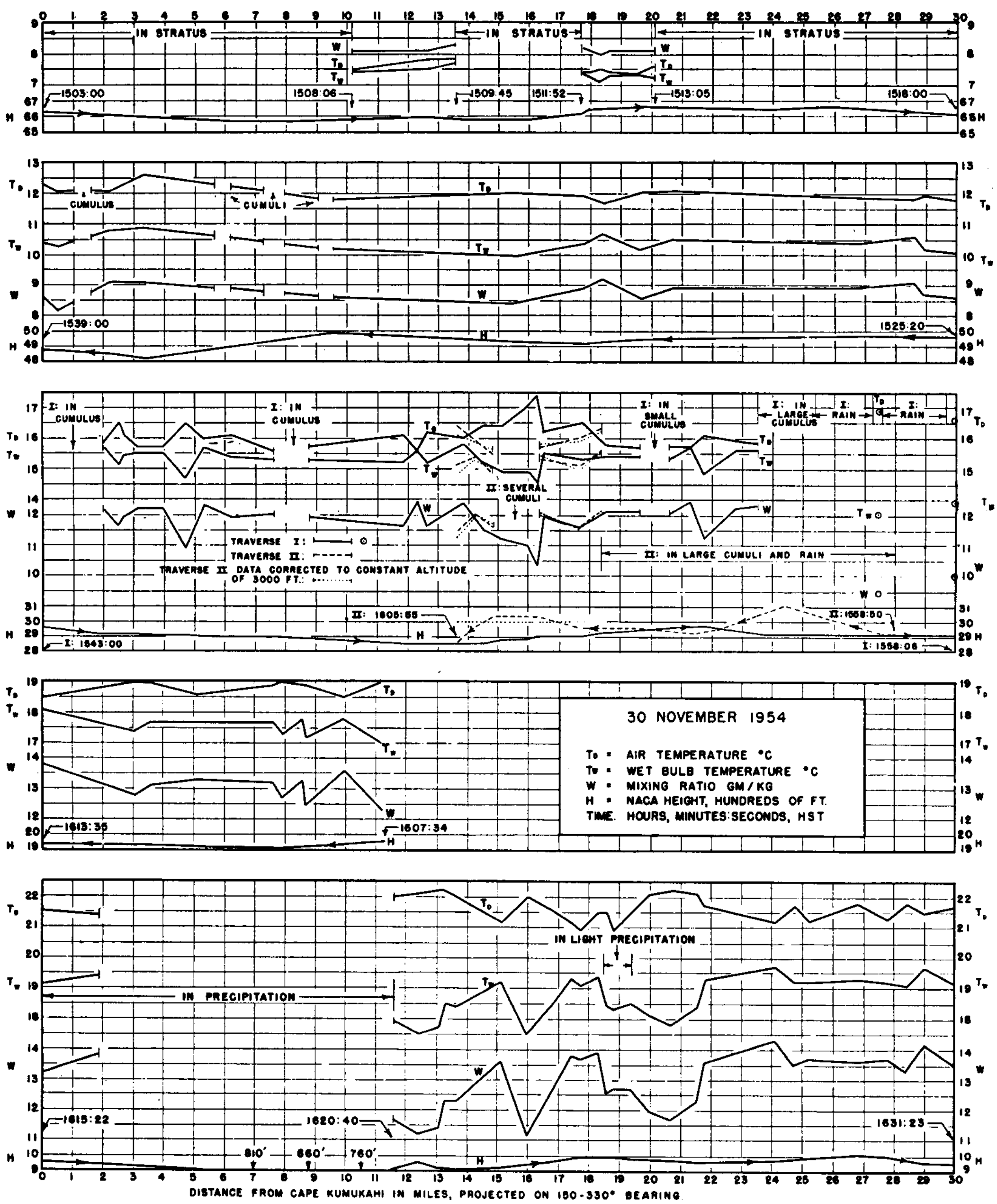

Fig. 6. Temperature and water vapor data obtained during the "budget" traverses made normal to the trade wind flow between Cape Kumukahi and Hakalau on 30 November 1954. Direction of flight is indicated by arrows on the height curves.

indicated a dry adiabatic lapse rate while the mixing ratio was not constant with height in the sub-cloud layer. Thus vertical displacements of air parcels would result in larger changes in the wet bulb than in the dry bulb temperature. These changes occur in periods as short as 6 sec which, at an air speed of 120 mi per hr, represents a distance of 0.2 mi.

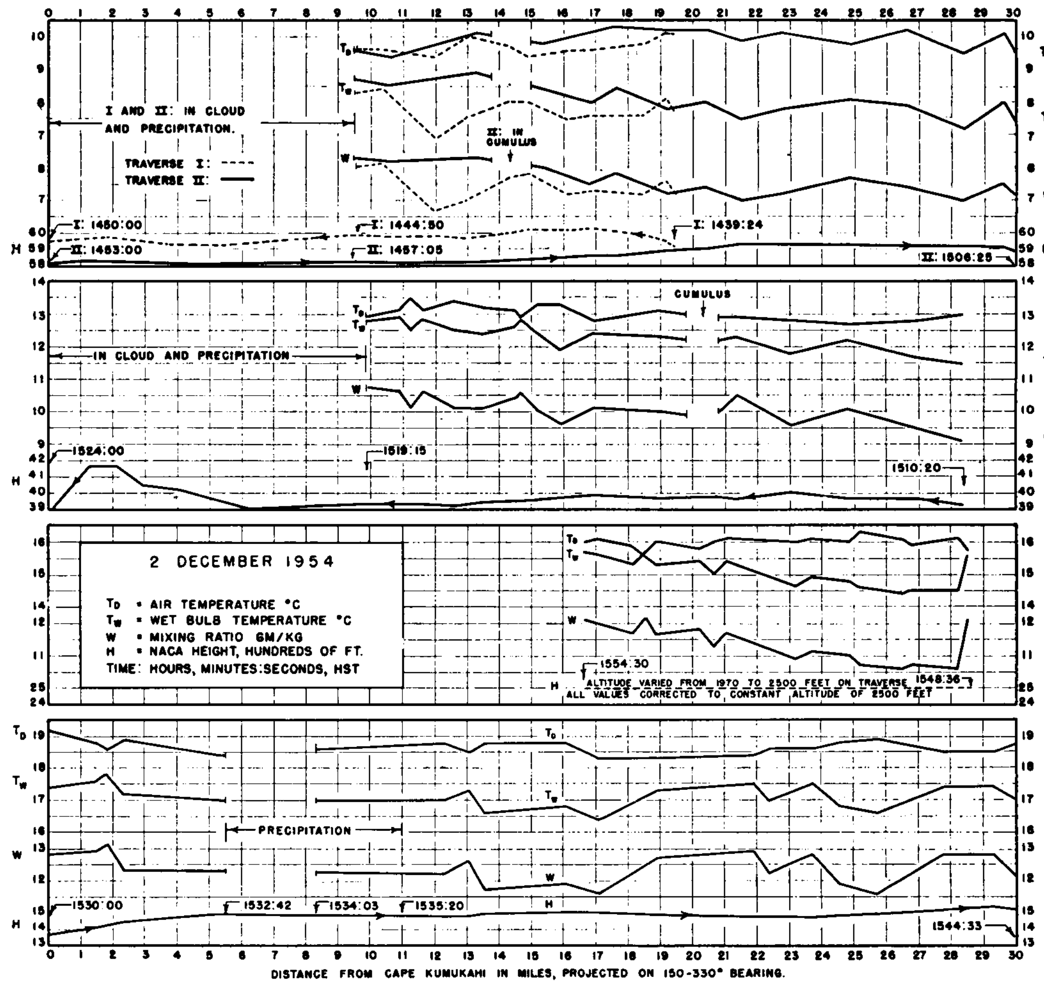

Fig. 7. Temperature and water vapor data obtained during the "budget" traverses made normal to the trade wind flow between Cape Kumukahi and Hakalau on 2 December 1954. Direction of flight is indicated by arrows on the height curves.

This is near the limit of resolution of the psychrometer, as the shortest change in temperature that can be reliably detected by the recording system is 4 sec.

The weather on 21 October was typical of trade wind conditions. The winds aloft taken at Hilo at 1100 HST[1] indicated a wind of 7 kts from 45 deg at 1,000 ft and a wind direction between 75 and 90 deg from 2,000 to 8,000 ft. Visual observations indicated that the surface winds were somewhat stronger and more nearly from the east over the sea upwind of the island. The orographic cloud was well developed and substantial rain fell on the mountain slopes (see MORDY and EBER, this monograph). The cumuli over the sea were of limited development, but increasing in size as they approached the coast. A pronounced line of small cumuli, oriented normal to the trade wind flow and moving with the wind, was observed from 26 to 17 mi off shore during the flight. A few light showers were observed off the coast during the flight. No correlation was observed between temperature and moisture and passage under the cumuli.

"Budget" flight data.—Figs. 6 to 8 present

[1] Hawaiian Standard Time, 150th meridian civil time, is abbreviated HST.

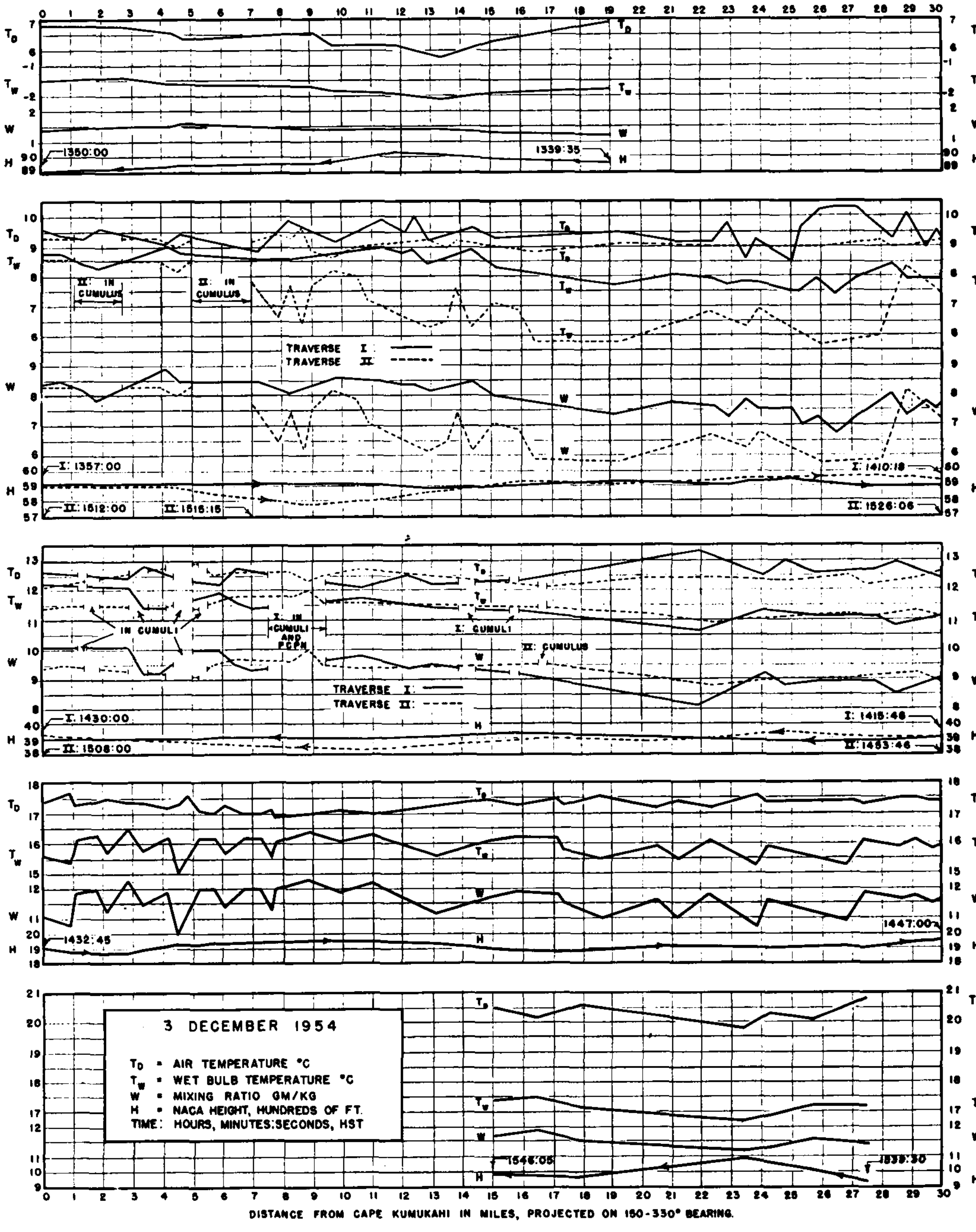

Fig. 8. Temperature and water vapor data obtained during the "budget" traverses made normal to the trade wind flow between Cape Kumukahi and Hakalau on 3 December 1954. Direction of flight is indicated by arrows on the height curves.

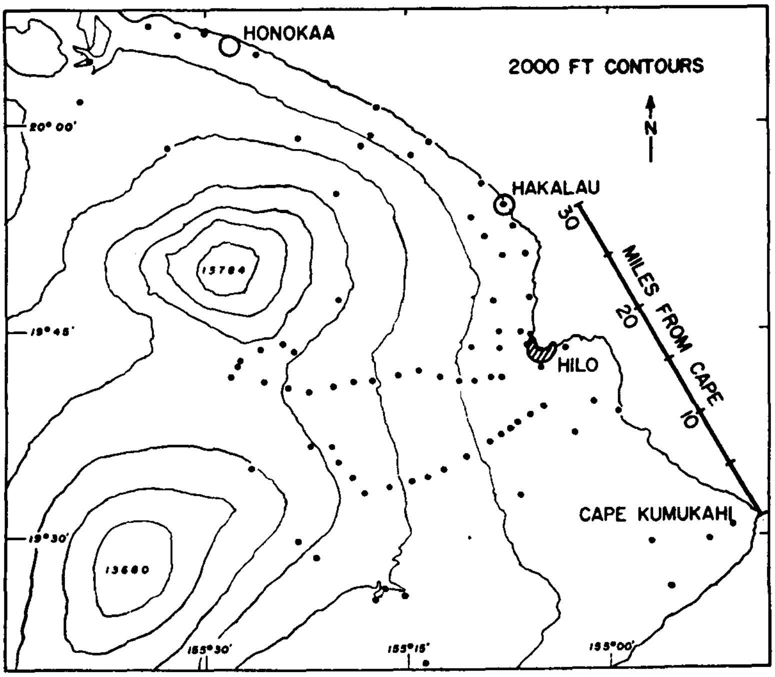

Fig. 9. The route flown during the traverses made on the "budget" days 30 November, 2 and 3 December 1954 in relation to the Island of Hawaii. The distance in miles from Cape Kumukahi is indicated along the traverse line. The dots represent the locations of the rain gages used during the project.

the temperature and water vapor data obtained during the traverses flown on the "budget" days. To aid in comparing the different traverses, the varying directions of flight were projected to a common bearing of 150—330 deg extending from the tip of Cape Kumukahi to a point off shore of Hakalau (see Fig. 9). Deviations from this bearing were usually less than 30 deg. All the data are plotted against the distance from Cape Kumukahi along the common bearing. Frequent times of observation are included to position the observations both in time and space.

It is difficult to determine how well these data represent the conditions of the air moving over the coast line during the entire period of each "budget" operation. An estimate can be made by comparing the traverses with the aircraft soundings and examining the data obtained when two traverses were made at the same altitude. It is seen that large variations over short distances occur in both temperature and water vapor content. These fluctuations appear to be short lived and not representative of average conditions. The largest fluctuations in dry and wet bulb temperatures were recorded on 30 November during the traverse at 1,000 ft. Temperature changes of 1 to 2° C over short distances were frequent, accompanied by changes in mixing ratio up to 25 per cent.

On many of the traverses, the plot of mixing ratio is a mirror image of the temperature curve. This indicates the presence of cells of ascending and descending air. A particularly good example is shown in Traverse I at 2,900 ft on 30 November (Fig. 6). The sounding on 30 November (Fig. 4 f) shows that the lapse rate of temperature was less than the dry adiabatic at 2,900 ft and the mixing ratio decreased with increasing height. Thus, a rising parcel of air would have arrived at 2,900 ft colder and with a higher mixing ratio than its environment, while descending air would be warmer and drier than its environment. Even though mixing would tend to neutralize these temperature and moisture differences, they often persist long enough to produce the "mirror image" pattern. This relationship was rarely observed above 4,000 ft. Using the sounding to determine the lapse rate of temperature and moisture at flight

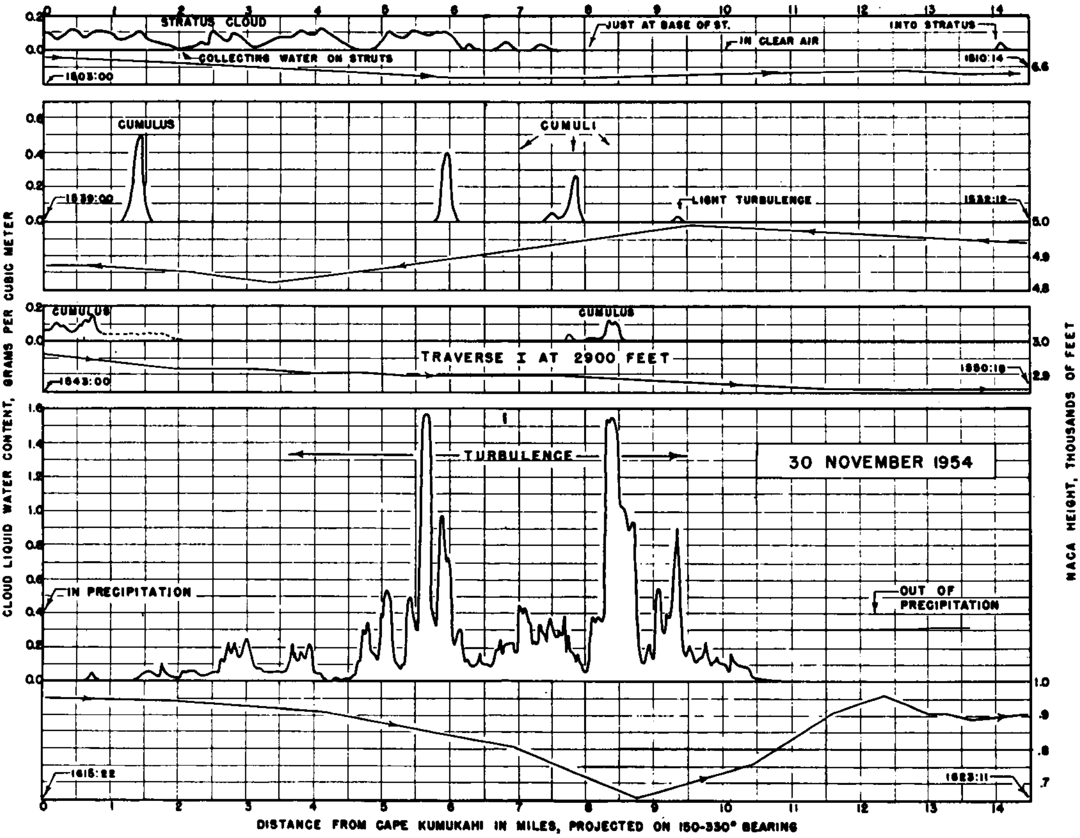

Fig. 10 a. Observations of cloud liquid water content obtained on 30 November 1954 during the "budget" traverses between Cape Kumukahi and 14.5 mi northnorthwest of the Cape. Times are indicated in hours, minutes, and seconds HST and direction of flight by arrows on the height curves.

level, a rough estimate can be made of the vertical displacement of these parcels as well as their horizontal extent.

The measurements of liquid water content in clouds encountered during these traverses are shown in Figs. 10 a, b to 12. Wherever available, comments on the type of cloud and occurrence of precipitation or turbulence are included in the figures. The indications of intensity of precipitation and turbulence are qualitative. The precipitation rarely appeared to be heavy enough to flood the tape in the water content meter thereby producing doubtful data. This appeared to have happened on part of the traverse at 800 ft on 30 November and at 4,000 ft on 2 December.

The liquid water content trace resulting from the collection of rain drops is "ragged" and usually rises in sharp spikes as seen in the traverse at 1,500 ft on 2 December (Fig. 11) and Traverse I, 2,900 ft, 26 to 29 mi from Cape Kumukahi on 30 November (Fig. 10 b). The instrument response to small cumuli of limited horizontal extent is typified by the trace shown in Fig. 10 a obtained at 4,900 ft on 30 November. This response is indicative of a single cell of rising air existing in each of the small cumuli. When flying through a large cumulus, which usually appeared to be composed of several smaller cumuli, the response indicates many of these cells, often overlapping and in varying degrees of development and dissipation. The trace obtained at 4,000 ft on 2 December (Fig. 11) is typical of this response.

The values of liquid water content are

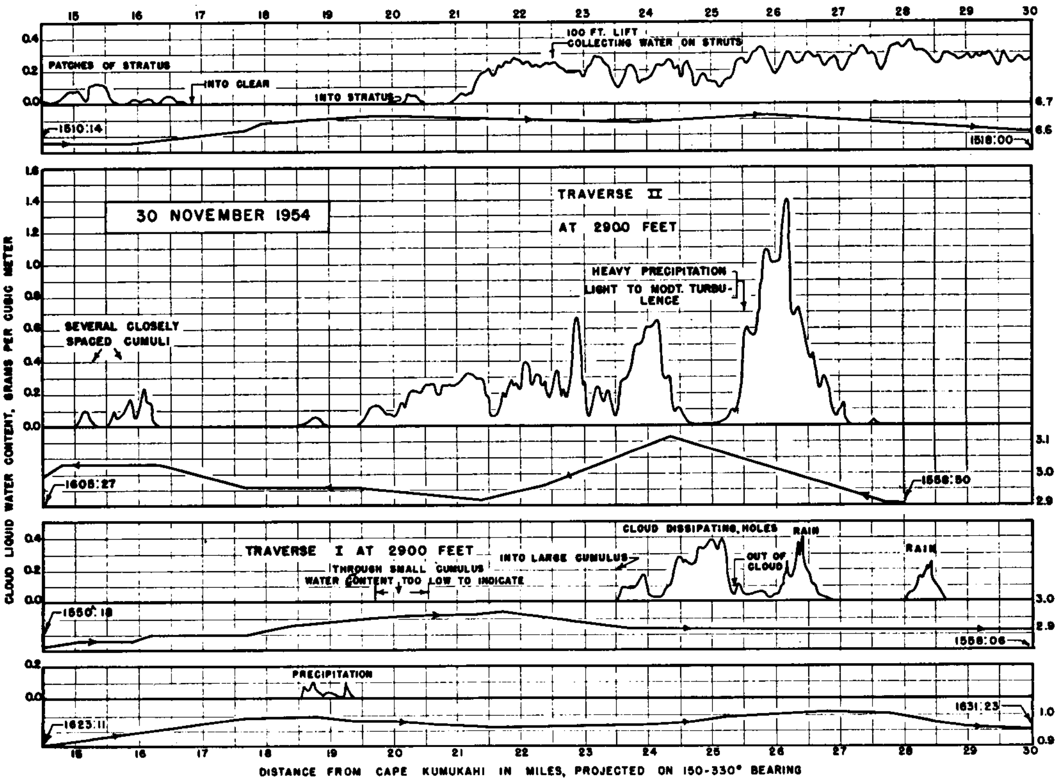

Fig. 10 b. Observations of cloud liquid water content obtained on 30 November during the "budget" traverses between 14.5 and 30 mi north-northwest of Cape Kumukahi. Times are indicated in hours, minutes, and seconds HST and direction of flight by arrows on the height curves.

typical for various types of clouds existing upwind of Hilo throughout the periods of the "budget" operations. However, the sampling of cloud water was not sufficiently random to permit the computation of the total horizontal flux of liquid water during the "budget" periods. Since the amount of water in liquid form is a small percentage of the amount in the vapor state, this should not hinder computation of the total water budget.

Distribution of cloud and showers.—On flights made upwind of the Hilo coast during "Project Shower", it was usually noted that the amount and size of clouds and number and intensity of showers observed were greater in the vicinity of Cape Kumukahi than in the region between Hilo and Hakalau.

The liquid water content data obtained on the traverses between Cape Kumukahi and Hakalau during the budget operations generally show higher peak values in the region up to 10 mi north of the Cape than on the remainder of the traverse to Hakalau. The only exception to this pattern was during Traverse II at 2,900 ft on 30 November (Fig. 10 a, b). No systematic variations in temperature and water vapor were observed along the traverses which would help to explain the variations in liquid water.

The distribution of rainfall over the eastern part of the Island of Hawaii usually showed a maximum on the mountain slopes in the Saddle area west of Hilo rather than in the vicinity of Cape Kumukahi as might be expected from these aircraft observations over the sea. However, a tongue of rainfall frequently extended from the maximum southeastward over the area to the west of the Cape. When the heavy orographic rainfall was absent, the rainfall contours reflect the passage of showers from the sea over the area between the Cape and Hilo.

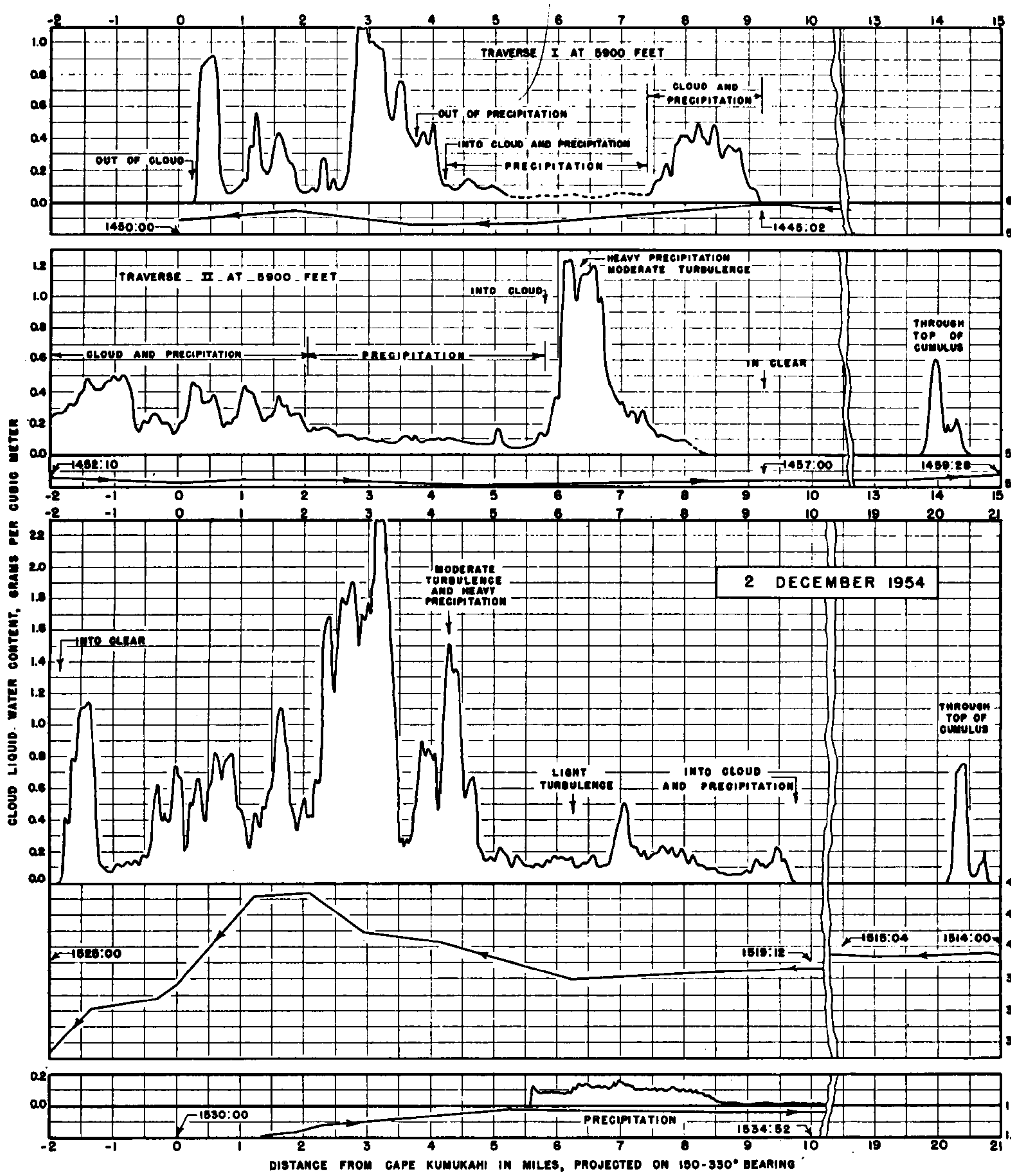

Fig. 11. Observations of cloud liquid water content obtained on 2 December 1954 during the "budget" traverses between Cape Kumukahi and Hakalau. Times are indicated in hours, minutes, and seconds HST and direction of flight by arrows on the height curves.

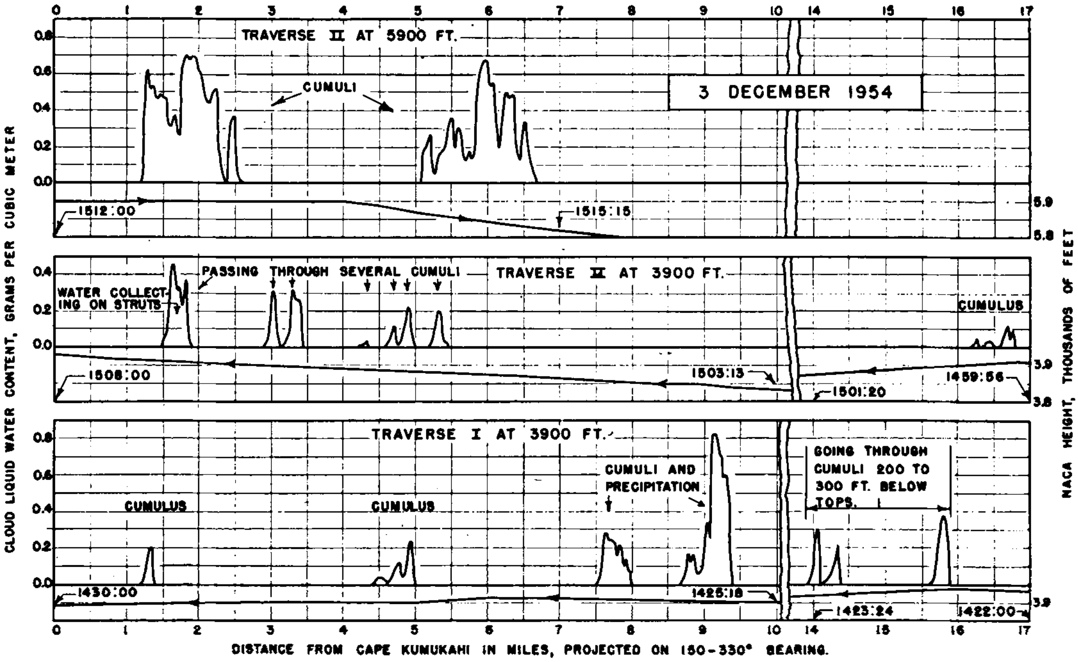

Fig. 12. Observations of cloud liquid water content obtained on 3 December 1954 during the "budget" traverses between Cape Kumukahi and Hakalau. Times are indicated in hours, minutes, and seconds HST and direction of flight by arrows on the height curves.

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