Some observations on the orographic cloud of the island of Hawaii and on trade wind cumuli nearby

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ABSTRACT

The results are described of some observations made from an aircraft of temperature and humidity (*a*) in the layer between the sea surface and the bases of trade wind cumuli to the windward of the Island of Hawaii, and (*b*) above and below the inversion surface from one side of the island to the other. From the latter observations some conclusion is reached regarding an upper limit to downwards mixing through the inversion.

Introduction

During the period of the U.S.–Japan cooperative program in Hawaii in the summer of 1965 the author made a number of short flights studying on a broad scale the temperature and humidity structure in the layer between the sea surface and the bases of the trade wind cumuli to the windward of the island. One longer flight was devoted to an investigation of the deepening of the moist layer between the surface and the base of the trade wind inversion which is associated with orographic lifting and cloud formation over the island. A brief outline of some of the results obtained is given below.

Description of equipment

The aircraft, a Cessna 336, owned and operated by Royal Hawaiian Air Service, was fitted with wet and dry bulb resistance thermometers in a housing under the starboard wing. These elements had a response time of about five seconds and their output was connected to a multi-point Leeds and Northrup recorder, as was the output from pressure transducers for altitude and air speed. Full scale deflection on the recorder represented 20°C and the starting point of the range could be changed in steps from -10°C to $+20$°C. Successive prints of each variable occurred every six seconds. Individual measurements have an overall accuracy of about ± 0.05°K in potential temperature and ± 0.05 g kg^{-1} in mixing ratio.

The orographic cloud

The cloud formations seawards and over the island on the afternoon of August 6 strongly resembled those observed during Project Shower in 1954. A panoramic photo of the orographic cloud taken at 1450 hrs from a position just seawards of Pepeekeo and an altitude of 11,000 ft is shown in Figure 1. As noted in Project Shower, one of the most striking features of the cloud system was the "wall" of convective cloud formed just leewards of the saddle, with tops rising nearly 3000 ft above the maximum height of the orographic cloud on the wind-ward side. It is noteworthy that on this occasion the cloud tops on the leeward side of the island, even well beyond the strongly convective region, remained at nearly the same high level; cloud base in this region was not measured.

Soundings were made between 1245 and 1645 hrs at positions indicated on Figure 2. The aircraft track was intended to follow the line of the wind on the basis of its value the previous day and during the early morning balloon flight from Hilo airport. However, the 1315 hrs Rawinsonde indicated a much more southerly component, the wind being roughly ESE and decreasing with height from 10 m sec^{-1} near the surface to nearly zero at the inversion level. On the windward side of the island the soundings were made from 11,000 ft to near the sea surface; in the saddle between Mauna Loa and Mauna Kea the minimum altitude was about 8000 ft, as was the case in a break in the con-

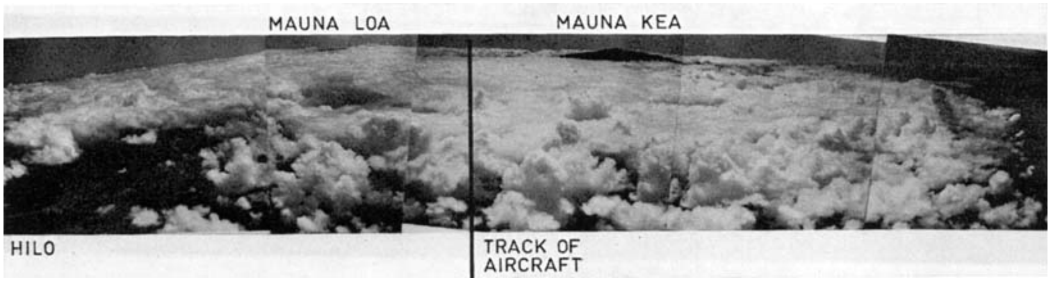


Fig. 1. Cloud over the Island of Hawaii viewed from 11,000 ft over Pepeekeo at 1450 hrs on August 6, 1965.

vective cloud in the vicinity of the saddle between Mauna Loa and Mt. Hualalai; over cloudy regions the aircraft descended to within about one hundred feet of cloud tops; due to lack of oxygen facilities in the aircraft the maximum altitude was restricted to 13,500 ft, and then only for brief periods, although it was realized that ascent to higher levels would have been desirable. Details of the results obtained at 1250, 1330, 1445 and 1505 hrs are given in Table 1.

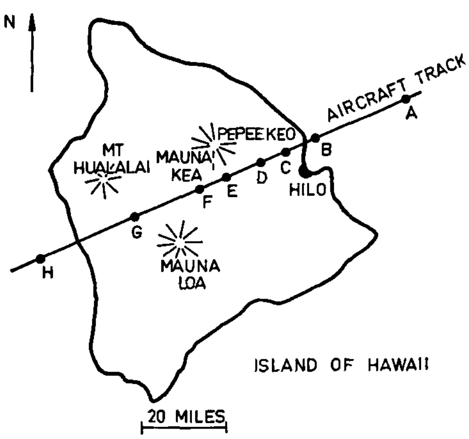
In general terms the picture that emerges from the soundings is as follows:

(*a*) In the layer between the sea surface and cloud base mixing ratio, potential temperature and wet bulb potential temperature are nearly constant with height.

(*b*) In the clear air between the seaward clouds there is a steady increase in potential temperature, a decrease in mixing ratio, but comparatively little change in wet bulb potential temperature as height increases.

(*c*) The top of the moist layer is marked by rapid decreases in mixing ratio and wet bulb potential temperature and an increase in the gradient of potential temperature. At this level there is thus a stable barrier between the lower air and the drier air above.

(*d*) At higher levels, the continuing low mixing ratio and increasing potential temperature with height are associated with a slow increase in wet bulb potential temperature.



POSITION OF SOUNDING	A	B	C	D	E	F	G	H
TIME	1250 1330 1350	1445 1645	1635	1625	1615	1505	1525	1545

Fig. 2. The positions of the soundings made on August 6, 1965.

Perhaps the most interesting conclusion from the soundings results from a study of the wet bulb potential temperature, a quantity which is closely conserved not only in adiabatic processes but also when water is precipitated into or out of the air mass. It will be observed from Figure 3, which shows isotherms of wet bulb potential temperature in relation to the position of clouds observed on the flight and the island contours, that the air immediately above the top of the orographic cloud is at a wet bulb potential temperature which differs little, if at all, from that of surface air to windward of the island and which must enter cloud base. It appears as if the whole depth of the cloud layer over the island is now well mixed, any decrease with height in mixing ratio being attributable to precipitation. It is of interest to see if the vertical structure of the wet bulb potential temperature can shed any light on the amount of mixing downwards through the inversion surface.

First, however, it is necessary to examine

Table 1. *Soundings at positions shown in Figure 2*

p (mb)	t_d (°C)	t_w (°C)	q (g kg^{-1})	θ (°K)	θ_w (°C)
Sounding A—1205 hrs					
963	20.60	18.72	13.48	296.98	20.15
952	19.60	18.22	13.40	296.89	20.06
944	19.16	17.59	12.88	297.22	19.78
935	19.49	15.56	10.35	298.33	18.17
925	18.77	15.31	10.48	298.55	18.33
917	17.89	15.06	10.64	298.36	18.41
908	17.22	14.78	10.71	298.56	18.53
899	16.30	13.54	9.77	298.51	17.74
889	15.69	13.66	10.30	298.79	18.25
880	14.97	13.24	10.23	298.96	18.25
869	14.47	12.73	10.00	299.53	18.24
859	14.14	11.90	9.32	300.13	17.88
851	13.57	11.37	9.09	300.39	17.77
843	13.37	10.40	8.23	300.97	17.23
835	12.87	10.42	8.53	301.24	17.56
826	12.93	10.38	8.57	302.29	17.93
818	12.60	10.18	8.59	302.75	18.10
809	11.94	10.29	9.08	303.06	18.62
803	11.94	9.77	8.61	303.71	18.43
793	11.43	9.05	8.18	304.19	18.22
787	11.30	8.83	8.08	304.72	18.30
780	11.12	8.22	7.61	305.40	18.12
772	10.67	7.59	7.25	305.78	17.94
766	9.76	6.79	6.90	305.49	17.53
758	9.00	6.42	6.94	305.55	17.58
752	8.38	6.15	6.80	305.68	17.65
746	7.78	5.94	7.10	305.63	17.74
740	7.50	3.95	5.44	306.13	16.44
734	7.03	3.30	5.10	306.23	16.17
728	6.77	2.35	4.44	306.67	15.69
724	6.49	1.49	3.86	306.88	15.21
719	7.28	−0.58	1.92	308.38	13.83
717	8.43	−1.49	0.78	309.96	13.24
711	8.51	−2.10	0.33	310.70	13.02
707	8.21	−1.99	0.56	310.90	13.34
703	7.99	−1.94	0.71	311.20	13.61
697	8.81	−1.86	0.48	312.88	13.99
693	9.06	−2.13	0.21	313.72	14.01
689	9.36	−2.09	0.17	314.44	14.18
685	8.70	−2.40	0.21	314.32	14.22
680	8.47	−2.55	0.22	314.74	14.37
675	8.40	−2.72	0.15	315.36	14.52
673	8.51	−2.90	—	315.71	14.48
668	7.71	−3.18	0.14	315.50	14.54
666	7.32	−3.32	0.21	315.30	14.54
Sounding A′—1330 hrs					
1015	24.69	21.06	14.16	296.58	20.51
1007	24.29	20.78	14.05	296.83	20.51
1002	23.81	20.64	14.15	296.80	20.57
996	23.33	20.40	14.11	296.82	20.55
990	22.76	20.30	14.31	296.76	20.68
984	22.33	20.01	14.18	296.86	20.61
979	21.86	19.87	14.26	296.82	20.66
974	21.43	19.62	14.17	296.85	20.61
970	21.04	19.38	14.07	296.75	20.50
964	20.64	19.15	14.02	296.88	20.51
958	20.15	18.83	13.88	296.92	20.42
953	19.72	18.79	14.09	296.94	20.58
948	19.32	18.25	13.62	297.00	20.25
943	19.07	17.62	12.97	297.21	19.84
939	19.12	15.62	10.54	297.65	18.09
933	19.25	14.37	9.09	298.32	17.13
Sounding B—1445 hrs					
924	18.35	16.24	11.81	298.19	19.26
916	18.12	15.55	11.17	298.76	18.94
908	17.17	15.39	11.48	298.51	19.10
899	16.73	14.38	10.58	298.57	18.51
884	15.71	14.30	11.11	299.30	19.06
875	15.11	13.73	10.80	299.61	18.91
867	15.40	12.99	9.93	300.67	18.55
858	14.13	12.74	10.28	300.20	18.69
852	13.85	12.41	10.10	300.51	18.64
845	14.13	11.87	9.48	301.59	18.48
837	14.02	11.57	9.29	302.27	18.53
829	13.19	11.12	9.24	302.29	18.49
821	12.76	10.35	8.68	302.64	18.15
812	12.42	9.85	8.40	303.20	18.09
804	12.14	9.57	8.32	303.83	18.22
796	11.61	9.58	8.63	304.11	18.56
789	11.06	8.76	8.09	304.28	18.16
781	10.39	8.76	8.46	304.52	18.54
772	9.80	8.73	8.78	304.84	18.89
766	9.25	8.38	8.71	304.93	18.86
760	8.85	8.01	8.57	305.19	18.82
752	8.76	7.70	8.38	306.09	18.95
746	8.40	7.21	8.11	306.40	18.82
740	7.99	6.94	8.08	306.67	18.87
731	8.04	6.35	7.57	307.75	18.79
725	7.54	4.57	6.14	307.94	17.64
717	8.92	−0.62	1.24	310.40	13.88
711	8.63	−1.55	0.70	310.93	13.51
704	8.33	−1.82	0.66	311.47	13.66
696	8.01	−1.60	1.01	312.11	14.24
691	8.22	−1.82	0.79	313.00	14.34
685	8.41	−2.14	0.52	314.00	14.41
680	8.33	−2.53	0.29	314.59	14.39
673	8.31	−2.74	0.19	315.48	14.60
668	7.98	−2.95	0.20	315.81	14.72
664	7.63	−3.19	0.19	316.00	14.77
660	7.34	−3.39	0.19	316.14	14.81
658	7.07	−3.55	0.19	316.20	14.83
657	6.91	−3.65	0.19	316.13	14.80
Sounding F—1505 hrs					
743	9.40	8.61	9.18	307.79	20.08
740	9.18	8.07	8.74	307.96	19.79
734	8.44	7.67	8.71	307.87	19.74
727	8.13	7.01	8.24	308.37	19.52
719	7.55	6.24	7.79	308.68	19.25
713	7.16	5.83	7.62	308.99	19.20
706	6.88	5.13	7.13	309.54	18.97
701	6.27	5.28	7.59	309.51	19.33
693	6.11	4.47	6.96	310.33	19.07
687	5.48	4.13	6.96	310.39	19.09
681	5.95	2.02	4.92	311.71	17.77
671	5.42	1.40	4.69	312.48	17.82
668	6.35	−3.76	0.26	313.98	14.11
662	7.22	−3.49	0.15	315.77	14.64

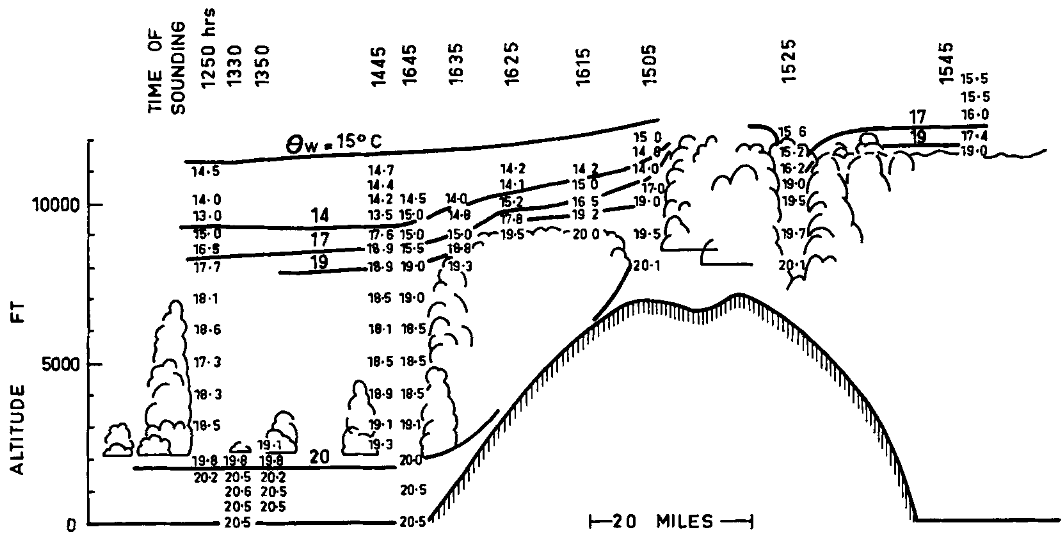


Fig. 3. Wet bulb potential temperatures obtained from the soundings made on August 6, 1965. The figure shows schematically the approximate position of the clouds encountered on the flight. The sounding made at 1505 hrs was made in a well-defined clear space in the region of the saddle but that made at 1525 hrs was in a temporary break in the convective reigon that did not extend down to the surface.

whether the island provided an additional source of heat that could significantly affect the wet bulb potential temperature of the air mass travelling over it. If we consider the heat flux from the surface is 250 watts metre^{-2}, which goes into heating an air mass 2 km deep for the period of two or three hours in which it moves from the coast to the saddle, then the heat added will be about 0.25 cal gm^{-1}, If this was supplied to cloudy air saturated at 10°C containing 1 g kg^{-1} of liquid water and at a pressure of 850 mb its temperature would rise by about 0.3°C. It seems unlikely, in view of the almost complete cloud cover observed, that the heat flux from the surface would approach this value; thus the air temperature, or wet bulb temperature, within the cloud layer is probably little changed as a result of surface heating.

Now the wet bulb potential temperature of the air above the inversion is about six degrees lower than that of the surface air and of the air at the upper surface of the island cloud. Mixing one part of this dry air of wet bulb potential temperature 14°C with ten parts of surface air of wet bulb potential temperature 20°C would result in air having a wet bulb potential temperature close to 19.5°C; one part in five would produce a temperature of about 19°C, well below that at the level of the cloud tops. Further, there is no indication of a progressive decrease in wet bulb potential temperature at any level within the cloud layer as the air moves inland from the coast. Although the observations were limited, being also restricted to clear air, and we have assumed for the wet bulb potential temperature conservation during adiabatic lifting and precipitation and a linear relationship in the mixing process (neither of which assumptions being strictly valid), it appears certain that less than 20%, and probably less than 10%, of the cloudy air originated above the inversion during the passage of the whole air mass over the island.

Downwards mixing processes are, therefore, quite slow in terms of the island clouds, though computation of mixing rates is not possible without a better knowledge of the wind structure over the island than is at present available. Measurement of the airflow and the surface heat flux, together with more detailed observations along the lines described above, preferably in cloud as well as in clear air, would, however, seem to offer the possibility of obtaining a quantitative value for the mixing rate downwards through the inversion.

The sub-cloud layer

Ten flights were devoted to observations of temperature and humidity patterns in the layer between the sea surface and the bases of the trade wind cumuli 50 to 100 miles to windward of the island. The flights usually consisted of a 40-mile horizontal traverse along the line of the wind (or cross-wind) at a height of 200 ft, followed by a reciprocal flight about 200 ft below the level of cloud base; sometimes flights were also made at intermediate levels. The flight pattern was designed so that, in the absence of shear, successive traverses would be vertically above each other, the whole pattern drifting with the wind. Soundings were made, during which the aircraft made a slow spiral ascent or descent, at each end of the horizontal track, and at other portions of it that were of interest, generally ranging in height from about 50 ft above the sea surface to cloud top levels.

As mentioned earlier, potential temperature and mixing ratio were nearly constant with height in the lower levels. However, a careful study of the observations shows that there is a gradient in potential temperature averaging 0.1°K km^{-1} and in mixing ratio of -0.6 g kg^{-1} km^{-1}. These values lead to a nearly neutral density gradient but produce changing values of the lifting condensation level for the sampled air at each height; the gradient in this latter quantity is about 100 m km^{-1}.

Organization of the clouds into lines was apparent in greater or lesser degree on half the flights made; on three other flights there was little or no cloud and on the remaining two flights extensive heavy showers and unevenness of cloud base levels made interpretation of the observations impossible. The results of only one flight, on which organization was marked, will be given here.

On August 3 the air within the cloud layer was fairly dry and cloud depth was everywhere less than 3500 ft and was usually 2000 to 2500 ft. Only drizzle, which did not reach the sea surface, was observed. Winds at Hilo ranged from 3 to 5 m sec^{-1}, changing from a northerly at the surface to north-easterly in the cloud levels. Fairly well defined lines of cloud were observed running roughly N–S and spaced about 25 miles between their centres. The cloudy regions were generally restricted to about 5 miles in the E–W direction with very small clouds extending

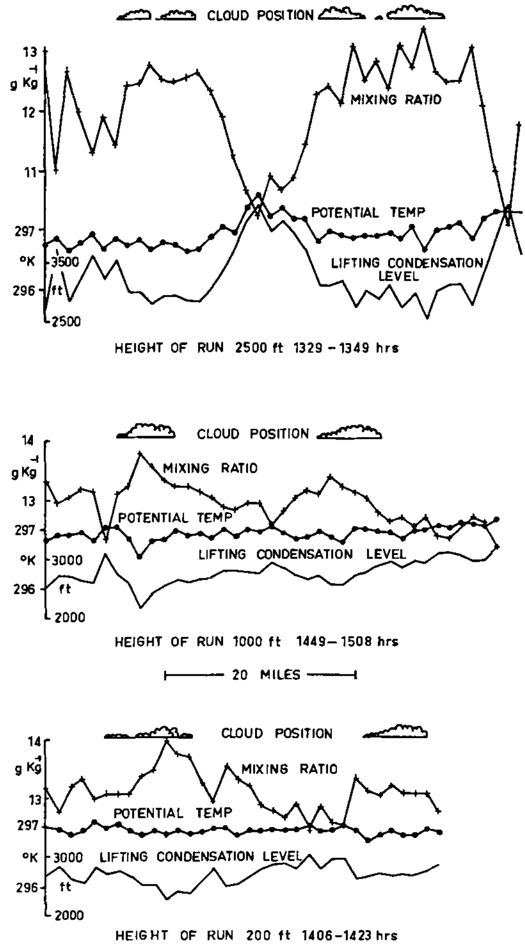


Fig. 4. Mixing ratio, potential temperature and lifting condensation level on three horizontal traverses, roughly vertically above each other, under cloud lines on August 3, 1965, some 50 miles to windward of the Island of Hawaii. Cloud base was at 2650 ft.

up to 5 miles further on each side; the central regions between lines were quite cloudless. Values of potential temperature, mixing ratio and lifting condensation level taken at half-minute intervals from the recordings are shown in Figure 4. Marked changes in mixing ratio were observed at all levels, with maximum values under cloudy regions, but no significant changes in potential temperature were observed at the lowest level. The spiral soundings showed the gradients in potential temperature and mixing ratio described earlier. This can be seen from the observations obtained during the horizontal traverses, though here temporal changes of the order of 0.2°K hr^{-1} and 0.2 g kg^{-1} hr^{-1} are also apparent.

It seems certain that the lines of cumulus clouds can continue to form only in rising air, implying that the air between the lines is descending. The observations under cloudy regions of air having properties similar to those at the surface and of drier air between the cloud lines with properties similar to those of air from higher levels are consistent with this picture, though, of course, they give no information about the mechanism whereby this circulation is imposed. Since the air temperature is nearly constant close to the surface it is likely that the sea surface temperature is also nearly constant from place to place and the large increases in mixing ratio in the low level air under cloud lines are due to the air having spent a longer time close to the sea surface than is the case for the air in the clear regions.

НЕКОТОРЫЕ НАБЛЮДЕНИЯ ОРОГРАФИЧЕСКОЙ ОБЛАЧНОСТИ НАД ОСТРОВОМ ГАВАЙИ И КУЧЕВОЙ ОБЛАЧНОСТИ ПАССАТОВ

Описаны результаты некоторых наблюдений, сделанных с самолета, температуры и влажности (а) в слое между поверхностью моря и основанием кучевых облаков пассатов с наветренной стороны острова Гавайи и (б) выше и ниже поверхности инверсии над островом. На основании последних наблюдений получены выводы относительно верхнего предела перемешивания, проходящего сверху вниз через инверсию.