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AIRFLOW IN THE LEE OF THE KOHALA MOUNTAINS

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The "rotating cloud of Kohala Mountain" has long been known locally as a special lee feature of trade wind flow past the Kohala Peninsula at the NW tip of the Island of Hawaii. Two periods of field observation have enabled us to identify the important roles of anabatically assisted sea breezes, the foehn winds that sweep downslope behind the Kohala ridge, and a slant line vortex. We believe that this slant vortex is generated over the steep slopes above Waimea at the southern end of Kohala Mountain and disappears where it crosses the coast in a narrow zone of strong horizontal shear between the trade winds which blow unaffected over the north of the Peninsula and the sea breezes to the south.

1. INTRODUCTION

Kohala Mountain dominates on the peninsula in the northwest of the Island of Hawaii and is of middle height for that island (Figure 1). Its ridge rises from sea level at Upolu Point in the north to a height of 1600 m after about 20 km, maintains this elevation for a further 6 km and then drops sharply to the Waimea Saddle at 800 m situated between Kohala Mountain and Mauna Kea (4206 m).

The position of the island in the tropics and the presence of mountains with various heights to above 4 km result in the island possessing a diversity of climate. The northeast part of Kohala Mountain is covered with forest and exposed to strong and persistent trade winds, while the leeward or southwest side is sparsely vegetated. The ruggedness on the

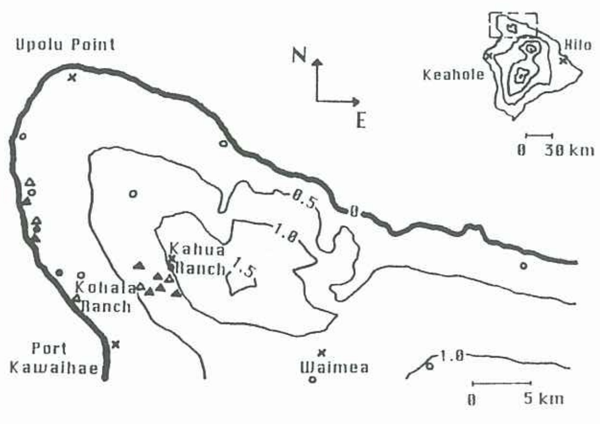

Figure 1: Map of the Kohala peninsula showing data sites from 1990 (○ - AWS, △ - pibals), 1991 (● - AWS, ▲ - pibals) and for AWS for both years (×).

windward side and semidesert in the lee have undoubtedly a significant impact on the circulation of winds around Kohala.

During the Hawaiian Rainband Project (HaRP) in July and August 1990 a number of interesting features were observed in the winds around Kohala Mountain. As a result, a more detailed field experiment known as the Hawaiian Lee Observation experiment (HaLO) was undertaken in July and August 1991.

The widespread network of instrumentation in 1990 throughout the whole peninsula and elsewhere on Hawaii, comprising PAMS automatic weather stations, omegasonde soundings and pilot balloon ascents, provided background data for a more concentrated study in 1991 using pilot balloons and automatic weather stations (AWS) concentrated in the lee of Kohala Mountain (Figure 1).

2. OBSERVATIONS

Wind circulation around the island of Hawaii and in its vicinity has been studied broadly (Mendonca, 1969; Nickerson and Dias, 1981; Smolarkiewicz, Rasmussen and Clark, 1988; Rasmussen, Smolarkiewicz and Warner, 1989), although scarce attention has been devoted to phenomena over the Kohala peninsula in view of its relatively modest height and extent. The study closest to our area of interest, is that of Schroeder (1981) who analysed sea breeze development on the slopes above Kawaihae Bay.

2.1 MAIN FLOWS

Lavoie (1967) identified four factors playing a significant role in controlling winds around the Island of Hawaii:

a) the strength of the trade or other synoptic-scale winds;

b) the height and intensity of the trade wind inversion;

c) the forced divergence of synoptic-scale winds around the high mountains of the island;

d) the daily heating and cooling cycle.

Figure 2 shows typical winds at 1200 LST over a network of PAM stations maintained around the Kohala Peninsula for the 1990 HaRP field experiment.

The trade winds blow predominantly from E to ENE depending on synoptic conditions. A diurnal variability in the strength of the trades is evident with a minimum of about 3-5 m/s occurring under normal mesoscale conditions at night-time, and maximum up to 10-12 m/s between midday and early afternoon LST. The trade inversion is typically at a height of approximately 2 km during the day-time and due

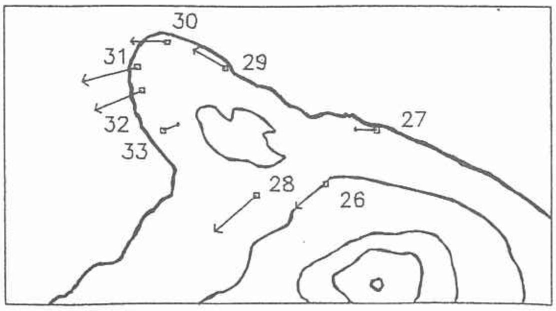

Figure 2: Typical daytime winds at PAM stations during HaRP, 1990. Winds are not given at stations where the winds varied considerably with date.

to its presence the trades are deflected partially to the north and south of Kohala Mountain and lifted partially over its crest as shown in Figure 2. The ruggedness of the northeast ranges generally decelerates the trades at lower levels, but wind speeds peak over the summit ridge. The trade winds commonly produce a line of foehn cloud along this ridge, and there is steady light precipitation within the cloud and a strong (10-15 m/s) dry surface foehn wind to the lee of the ridge.

Trades deflected to the south of Kohala accelerate as they are funnelled through the Waimea gap, through which they pass at the relatively high speed of about 10 m/s. We will suggest that there is strong and concentrated generation of vorticity around the steep southern slopes of Kohala Mountain and that this vorticity is turned into the streamwise direction as it is advected into the lee of the mountain. (See Mason and Morton, 1987, for related studies of flow past obstacles.)

Flow on the lee slopes is strongly influenced by the daily heating and cooling cycle. Due to differential heating and cooling, land or sea breezes and anabatic or katabatic slope flows often develop. These slope flows vary daily in response to synoptic and local atmospheric factors. Under clear conditions, the downslope nocturnal flow on the leeward side of Kohala Mountain which is a combination of land breeze and katabatic flow, changes soon after sunrise to an upslope flow due to strong temperature gradients caused by vigorous surface heating. Under day-time heating the upslope flow, a combination of sea breeze and anabatic effects, generally dominates over the lee slopes.

Land and sea breezes typically affect the local climate over the southern part of the peninsula in the neighbourhood of Port Kawaihae, but a completely different picture is presented over the more northerly leeward coast. Strong and steady trades blowing over the low ranges of the mountain cut off the sea breeze from the north, containing it more or less to the south. The existence of strong trades to the north and the presence of sea breezes to the south results in a shear layer in the lower atmosphere which produces a visible shear line on the sea surface. This line separates the two opposite flows. The Kohala shear line is shifted alternately north or south along the coast depending on the strength and direction of the trade winds, the heating of the lee slopes and the atmospheric stability.

2.2 DATA

Regular radiosonde ascents are made at Hilo and Lihue and twice daily soundings were recorded for the field periods in 1990 and 1991. Surface data were obtained also from networks of AWSs during both HaRP and HaLO. These data were analysed to identify those days that differed from the prevailing trade winds due to the influence of disturbances. A disturbance observed across these networks may be regarded as synoptic in scale. The results of these analyses are presented in Figure 3 and show that the observational period of 1991 was affected by many more synoptic disturbances than 1990.

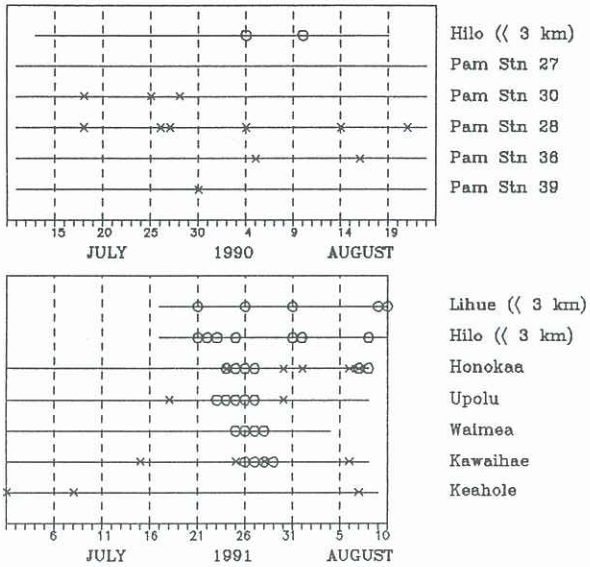

Figure 3: Days of departure from normal trade winds for the observational periods in 1990 and 1991.

Over 110 pilot balloons were launched in the lee of Kohala both along the coast and on the slope of the mountain, and these provided detailed information about the vertical structure of the airflow. Balloons launched from the coastal region showed weak to moderate sea breezes up to 7 m/s reaching heights of 0.5-1.5 km with reversion to trade winds at greater heights. Flights from the middle of the leeward slopes, however, showed a more confused layer of reversing flows between the sea breeze and the upper trades (Figure 4).

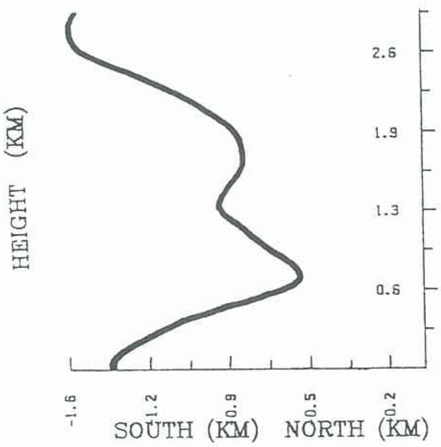

Figure 4: A north-south cross-section of the pibal trajectory observed on 3 August 1991 at 1540 LST depicting the typical layering effect in the lee of Kohala Mountain.

Behind the ridge, the upslope flow meets the trades head-on resulting in a vertical updraft of about 5 m/s along the convergence line. A sea breeze cloud line was often observed in the moist rising air close to the west of the convergence line appearing in an arc during late morning or midday and often persisting to late afternoon.

3. ANALYSIS AND DISCUSSION

Our observations suggest that there are three main factors which determine the flow on the lee slopes of the Kohala Peninsula:

- strong, steady and predominantly ENE trade winds;
- anabatically enhanced lee sea breeze circulation, with surface upslope flow usually from the SSW;
- the intermediate mountain barrier which partly diverts the incident trade winds below the trade inversion and partly lifts them over the Kohala ridge.

The last factor seems to be a decisive one as is shown later in our discussion.

3.1 THE CLOUD CONFIGURATION

Some major flow features observed were quasi two-dimensional and are illustrated in Figure 5. The figure is an idealised NE-SW cross-section of the lee flow, showing I the descending foehn, II the anabatic/sea breeze flows and III the cloud line exhibiting a clockwise circulation coupled with axial flow to give a corkscrew-like motion.

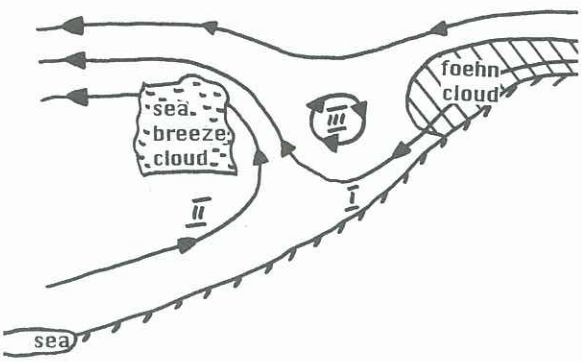

Figure 5: Indicative 2-D streamline pattern of the vertical cross-section in the lee of Kohala. The sections are: I - foehn wind; II - anabatic/sea breeze flows; and III - the rotating cloud of Kohala Mountain.

A common cloud configuration comprised the foehn cloud oriented NW along and to the NE of the summit ridge, an arc of sea breeze cloud a little north of west, and a third line often observed in the wedge of clear air between these two. The foehn wind of 10-15 m/s to the lee of the summit ridge plunged downslope and then lifted over the sea breeze front. The third cloud consisted of a line that could be identified first near the Waimea shoulder of Kohala and that extended to the WNW through the wedge of clear dry air upslope of the sea breeze front. The third cloud exhibited clearly visible circulation about its axis, clockwise in the NW sense, coupled with axial flow to yield a corkscrew-like motion diagonally across the main flow towards the coast. This cloud is well-known locally as "the rotating cloud of Kohala Mountain"; its motion was revealed by several pilot balloon flights (Figure 6). On

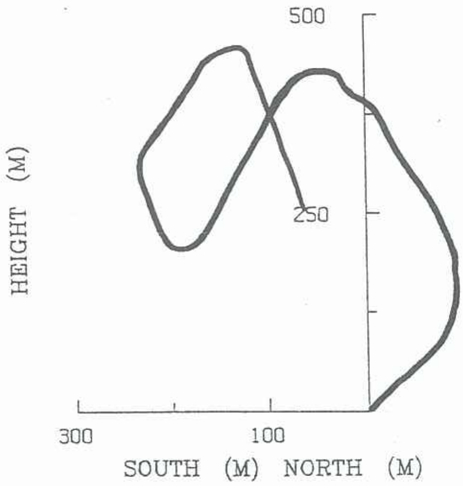

Figure 6: The trajectory of the pibal flight on 12 August 1990 showing a loop, which is caused by a strong updraft and downdraft at height 300m above the ground.

some occasions it was the only feature of the entire lee flow with any cloud marking and its wisps of cloud were at times violently distorted in a swirling axial flow.

3.2 POSSIBLE EXPLANATIONS

The problem of the flow past bluff bodies is difficult to solve analytically because the equations are highly nonlinear and three-dimensional, so studies have concentrated on laboratory experiments (Hunt and Snyder, 1980; Mason and Morton, 1987) and numerical simulation (Mason and Sykes, 1979 ; Mason and Morton, 1987).

In the present case three possible explanations might be proposed:

(i) that there is a hydraulic jump behind Kohala Mountain;

(ii) that the observed pattern of cloud lines is due to lee waves;

(iii) that the third cloud line marks a "lifting line vortex" generated from the mountain surface and relating to a transverse wind force on Kohala Mountain.

We argue that the observed flow is a combination of a lifting line vortex generated from the steep slopes above Waimea, coupled with the foehn and sea breeze/anabatic winds.

The essential feature of the observed flow is the circulation-cum-axial-flow of the third cloud line, which we take from our observations to be a frequent and highly important feature of that cloud line. A hydraulic jump could not generate the observed vorticity nor the cross field axial flow, and there was little evidence of the level of turbulence to be expected in a jump of the amplitude indicated. There may have been some lee waves as indicated on occasion by a succession of cloud lines roughly parallel to the mountain ridge and extending out to sea, although on these occasions there was little evidence of a sea breeze and none of a slant "lifting" vortex.

We are led to ask whether there is any evidence that "lifting vortices" may be induced by flow past mountains. Mason and Morton (1987) have proposed exactly this kind of flow, and have presented numerical model solutions for flow past symmetric and skew hills to show that such trailing vortices exist. According to their argument the vorticity would be generated over the steep slopes of Kohala in the pressure gradient driven flow through the Waimea gap, and this vorticity would then be advected around the mountain and turned into the streamwise direction.

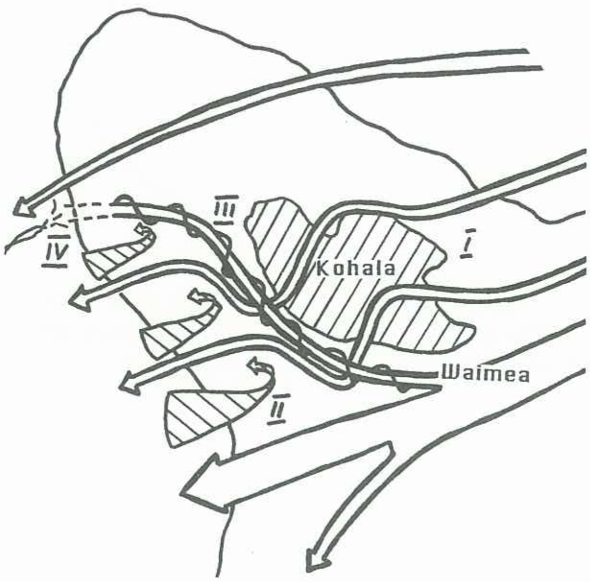

Figure 7: 3-D sketch of the prominent features of th flow past Kohala Mountain: I - trade wind flow; II - sea breeze/anabatic winds; III - trailing vortex; IV - dissipative region of the trailing vortex.

Region I in Figure 7 represents the trade winds that pass through the foehn cloud and blow as a surface flow over Kohala ridge. In the lee, these are blocked by sea breeze/anabatic winds II and lift strongly from the surface before turning out over the sea. The trailing vortex III with its roots over the steep southern slopes of Kohala above Waimea sits above the foehn/sea breeze confluence and extends diagonally across to a point above the coast where it loses its vortical organization in the strongly sheared region between the trades that cross the northern end of the peninsular and the strong sea breeze to the south. From the point at which the rotating cloud would have crossed the coast IV a pattern of disturbed water appears on the sea surface which with increasing distance rapidly simplifies to a single narrow dark shear line extending as far as the eye can see out over the ocean.

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