Air motions over the windward coast of the Island of Hawaii[1]

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ABSTRACT

Attention is called to the strong land–sea breeze regime which dominates local winds over the eastern slopes of the Island of Hawaii. An analysis is made of the diurnal variation of the winds measured at Hilo Airport by conventional soundings during the summer of 1965. The diurnal wind oscillation has a maximum range of over 6 m sec^{-1} at the surface and extends to an altitude of over 3 km. An example of the trajectory of a radar-tracked, constant volume balloon is analyzed to illustrate the combined effect of sea breeze and barrier deflection flow on the local winds measured over the slopes.

Introduction

The major topographic features of the Island of Hawaii together with some general aspects of the local climatology are discussed in an introductory article[2] in this collective set of papers dealing with the results of a cooperative study of cloud and rain mechanisms on the island. One purpose of this paper is to draw attention to the variability of winds in space and time brought about by local effects. Knowledge of the characteristics of these local air motions will be indispensable to a full understanding of aerosol distributions and of problems dealing with shower formation and life histories over the windward coast of the island.

The nature of airflow over a heated island is an important problem in its own right, and it is hoped that the observations reported herein will help to stimulate more extensive measurement programs.

The air motions around and over the Island of Hawaii at any given time result mainly from the interaction of four factors: the large scale synoptic wind field, the mountain barrier configuration, the intensity and height of the trade inversion, and the diurnal heating and cooling of the land. In some circumstances the exchange of latent heat in condensation and evaporation over the slopes may also exert a significant influence on the flow.

[1] Hawaii Institute of Geophysics Contribution No. 165.

[2] Background data for the Warm Rain Project, by R. L. Lavoie, pp. 348–353, *Tellus*, this issue.

The land–sea breeze at Hilo

The most obvious local disturbance of the prevailing flow is the daily rhythm of the mountain–valley, land–sea breeze. Under daytime heating the upslope sea breeze reinforces the trade flow, and extensive cloud cover typically develops over the windward slopes. During the night a thin layer of downslope flow prevails over the whole mountainside (see e.g. Price & Pales, 1963), but showers, perhaps generated in the coastal convergence zone at the meeting with the trades, can still move upslope imbedded in the trade flow aloft. Although considerable insight into the nature of the interaction between this diurnal circulation and the trade winds has been provided by Leopold (1949), a much deeper understanding is needed before the mesoscale distribution of cloud and shower formation over the island can be predicted.

The character of the land–sea breeze regime as it affects the winds at the Hilo Airport can be seen from Fig. 1*a* prepared from hourly surface data and four-times daily wind soundings collected during the course of the joint summer project. The mean wind profile (Fig. 1*b*) has been subtracted in order to reveal the diurnal pattern. Since the diurnal oscillation takes place mainly in a vertical plane oriented along 70 degrees and 250 degrees, the east–west component depicted in the figure is representative. The land–sea breeze circulation extends to at least 3 km. It consists of an intense lower branch about 1 km thick and an upper return flow roughly twice as deep and half as strong. The upper branch

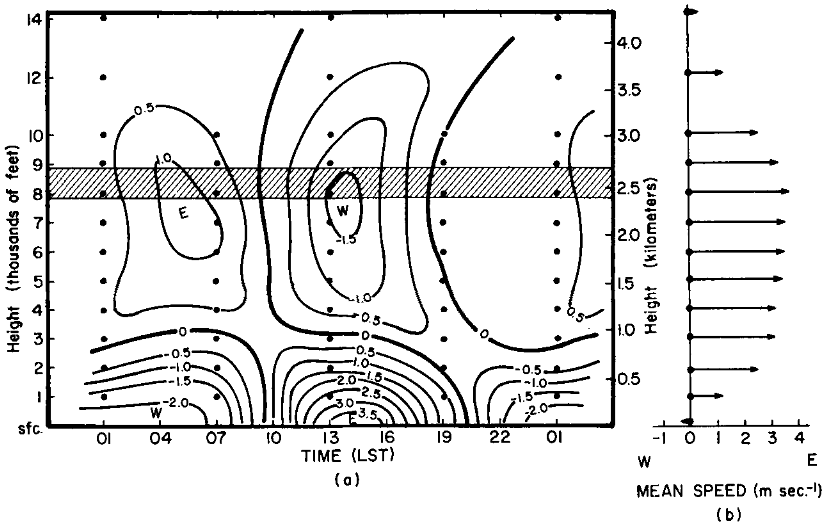

Fig. 1.(*a*) Diurnal wind regime at Hilo Airport, 11 July to 25 August 1965. Analysis of the deviation from the mean zonal component of the wind with time of day. Isopleths labeled in m sec^{-1}, positive for increased easterly component. Hatched layer represents median base altitude and depth of the trade inversion during this period. Dots show upperlevel data points upon which analysis is based. (*b*) Vertical profile of the mean zonal component of the wind during same 46-day period. Height scale corresponds to that in (*a*).

maximum is just below the median level of the base of the trade inversion, although its influence transcends the inversion (represented by diagonal hatching in Fig. 1*a*). There is no evidence that the height of the inversion layer at Hilo is influenced by the diurnal motion regime.

The oscillation just discussed is of course a disturbance superimposed on the prevailing wind whose mean profile during the same period is shown in Fig. 1*b*. Thus, for example, the night time "westerly wind" layer in Fig. 1*a* is not in fact 1000 m deep but is found only up to the altitude at which the downslope component ceases to prevail against the trades—about 380 m in the mean. Nevertheless, the westerly wind layer is very dependable; it failed to develop by 0100 LST on only one of forty-six days studied. In contrast, the westerly component induced in the cloud layer during the afternoon is usually evidenced only by a slackening of the trades at those layers, although the wind might actually be reversed by this effect under conditions of weak trade flow (see wind sounding on 6 August e.g., Fig. 4).

Constant volume balloon trajectories

During the joint summer program a pilot project was undertaken whose objectives included the elucidation of the sea breeze regime. The measurements were made using constant volume, helium-filled balloons which were ballasted to float at levels ranging from 500 m to 1500 m and tracked automatically by means of the M-33 radar system located at the Cloud Physics Observatory. The balloons were fabricated from sheets of plastic mylar about 0.025 mm thick and were fashioned into a pillow shape, 2 m long and 37 cm in diameter. They were essentially identical with those developed by the cloud physics group at The Pennsylvania State University and described by Booker & Cooper (1965). This latter paper also provides information on launching techniques which were followed here without significant modification. The balloons were flown in a horizontal attitude in order to maximize their response to vertical air motions.

A detailed discussion of flight computations and results is available in a project report describing the experiments (Lavoie, 1966), but a brief treatment of the results of a single flight will be provided here in order to further illustrate the characteristics of the daytime flow around Hilo.

The horizontal projection of the trajectory of a constant volume balloon launched from the

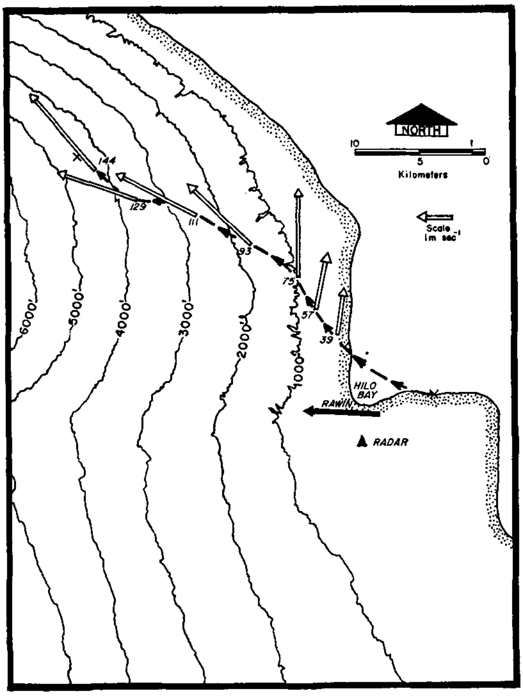

Fig. 2. Horizontal trajectory of the constant volume balloon launched from the shore of Hilo Bay at 1211 LST on 6 August 1965. Numbers along track are minutes after launching. Arrow labeled RAWIN refers to Airport wind at 1040 m (3400 ft) from the 1315 LST sounding (095 deg, 2.1 m sec^{-1}). Outlined vectors are winds along the trajectory expressed as a deviation from the airport wind. Short arrow labeled 1 m sec^{-1} is scaling length. Terrain contours in feet.

shore of Hilo Bay at 1211 LST on 6 August 1965 is shown in Fig. 2. The equilibrium float altitude of the balloon was about 1040 m (3400 ft), and the wind measured at this level by conventional vertical sounding over Hilo Airport at 1315 LST is represented by the solid vector in the diagram. The trajectory shows evidence of a pronounced barrier deflection effect in the airflow carrying the balloon. A closer examination reveals three rather distinct regimes in the trajectory. These are made more graphic by the sequence of arrows entered at 18-minute intervals along the track. These arrows represent the vector difference between the mean winds measured along the trajectory during successive 18-minute periods (each centered at the point where the arrow is plotted) and the winds measured by the airport rawinsonde at the corresponding altitude above sea level. The difference vector then represents the "island effect" relative to Hilo winds.

During the first 75 minutes of flight the balloon drifted in a clockwise gyral tending to parallel the island contours with time (as might be expected under purely barrier flow). Beyond minute 75, however, the airstream commenced curving slightly counterclockwise, moving more nearly upslope with time. At minute 132 the balloon changed course again and was moving nearly parallel to the contours when it was lost from the view of the radar. The explanation for the horizontal excursions of the balloon involves the relative importance of the sea breeze at various points along the trajectory and requires consideration of the balloon's elevation above the terrain.

Fig. 3 depicts the vertical trajectory as a function of time. Terrain elevation and cloud base height have been sketched in. A simultaneous photograph of the region traversed by the balloon is included in the paper by Warner (1967) in this issue. There were no clouds over the coastline, but the photograph shows a broken rampart of small cumulus clouds a few kilometers inland, parallel to the coastline. As the balloon approached these clouds at about 70 minutes after launch it was apparently caught in air subsiding at a rate of up to 1.4 m sec^{-1} near the edge of a cumulus. When the balloon reached the approximate cloud base level, visual contact (through the boresite telescope of the radar) was lost and it experienced a sudden updraft (at minute 79)—perhaps being drawn up into one of the clouds. Following the encounter with the outer cloud line, the balloon recovered its float altitude and suffered only minor convective upsets for the next 30 minutes, although from all visual appearances this part of the flight should have taken place in nearly continuous cumulus and stratocumulus cloud. There was, however, no indication of rain at any time along the trajectory.

As the balloon progressed inland the mountainside gradually "rose up" to meet the float level airstream, and interaction is noticeable after about minute 115 when the balloon was only about 180 m above the terrain. From minute 116 to minute 132 the balloon was ascending so as to remain at nearly constant height above the terrain; apparently the airstream was, at this level, following the slope

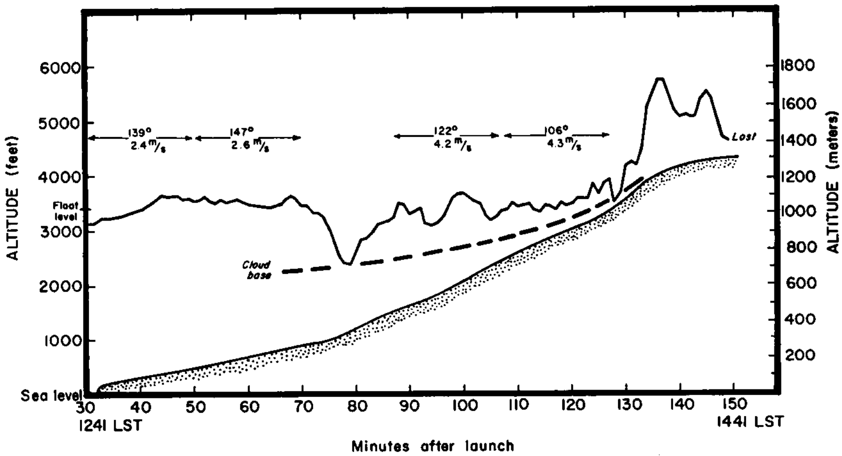

Fig. 3. Vertical trajectory of same balloon described in Fig. 2. Data taken from radar positioning at 1-minute intervals. Terrain profile is that of the lower flank of Mauna Kea.

quite closely. At about minute 132 a strong updraft (about 2.5 m sec^{-1}) was encountered, carrying the balloon to nearly 600 m above ground.

When the vertical trajectory is examined together with the expected structure of the sea breeze regime at 1400 LST given in Fig. 1*a* an explanation for the curious horizontal motions of the balloon suggests itself. If the sea breeze disturbance as depicted in Fig. 1*a* can indeed be considered to be superimposed upon the prevailing flow and to have similar structure over the lower slopes of Mauna Kea, one might expect that the airstream at near 1 km above ground would not "feel" the sea breeze. As the balloon approaches the mountain slope, however, it is driven upslope more and more strongly by the sea breeze circulation. Thus during the first 75 minutes of flight the balloon was moving with air that was reacting primarily to the effect of a barrier placed in its path. Beyond this point the balloon quickly came into rapidly increasing upslope motion as the elevation above ground decreased steadily. Thus, for example, at minute 93 it was only 425 m above ground and, from Fig. 1*a*, one would expect an additional 2.5 m sec^{-1} upslope component to come into play. This is about what is observed. Finally, at minute 132 the balloon was carried into a strong updraft and seemed to break away once again from the upslope sea breeze regime—which may be only about 300 m deep at this altitude on the mountainside.

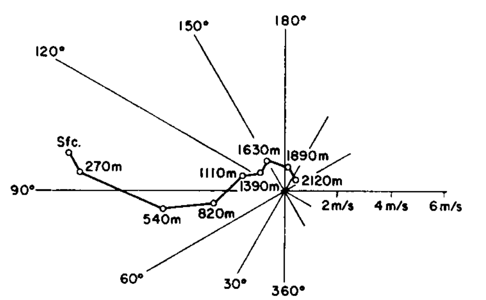

Fig. 4. Hodograph of Hilo rawinsonde on 6 August 1965 at 1315 LST from surface to 2120 m. Radial scale for wind speed shown on right.

To demonstrate that the change in flow pattern indicated by the trajectory is not due to vertical wind shear alone, the mean direction and speed of the balloon is entered for four 20-minute periods on Fig. 3. The trajectory altitude averaged 1050 m during each of the periods chosen, but the wind is seen to change significantly with time. Further evidence on this question is provided by the hodograph of the Hilo rawinsonde presented in Fig. 4. The vertical wind shear is seen to be quite small in the 900 m to 1400 m layer in which the constant volume balloon drifted.

Conclusions

A strong land–sea breeze regime is evident on the windward coast of the Island of Hawaii. The circulation extends to an altitude of at least 3 km at the coast and merges with a mountain-valley wind regime over the upper slopes to form an extensive diurnal oscillation which must interact to some extent with the prevailing large-scale airflow. For the most part, however, the large-scale flow is deflected around the island mountain barrier which rises well above the stable, inversion layer.

The results of the constant level balloon flight described above, together with several others made during August 1965, indicate that to a good approximation the *daytime* winds near Hilo can be considered to result from a simple superposition of an essentially reproducible sea breeze circulation and a barrier deflection flow. The latter component may be predictable from relatively simple models but will probably vary with the height of the inversion as well as with the orientation of the large-scale flow. The interaction of the trades with the land breeze may well be more complex, but constant level balloon trajectories have been shown to be a powerful tool in such a study.

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ДВИЖЕНИЕ ВОЗДУХА НАД НАВЕТРЕННЫМ БЕРЕГОМ ОСТРОВА ГАВАЙИ

Привлекается внимание к сильному бризу, который доминирует над восточными склонами острова Гавайи. Проделан анализ суточных изменений ветра, который измерялся в аэропорту Гило путем обычного зондирования летом 1965 года. Суточные колебания ветра имеют максимальный размах, равный 6 м/сек у поверхности земли, и простираются до высоты 3 км. Анализируется пример траектории прослеживаемого радаром баллона постоянного объема для иллюстрации комбинированного влияния морского бриза и потока, набегающего на препятствие, на местный ветер, измерявшийся над склонами.