PICTURE OF THE MONTH

Wave Clouds in the Vicinity of Oahu Island, Hawaii

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1. Introduction

Frequently, lee wave clouds are seen on SMS-2 satellite imagery extending downstream from the Koolau Mountain Range on the island of Oahu in the Hawaiian Islands. The Koolau Mountains (Fig. 1) are ideally situated for the generation of lee standing waves. Oriented NNW–SSE with ridge elevations from 600 to 940 m, the Koolaus are perpendicular to the prevailing northeast trade wind flow. Such waves also may be generated when the wind direction is reversed. This occurs infrequently and generally during the winter when the westerlies penetrate downward to the surface.

Scorer (1949) formulated a parameter L^2 which can be related to the wavelength of the lee waves and is defined as

$$L^2 = g\sigma U^{-2} - (\partial^2 U/\partial Z^2)U^{-1}, \qquad (1)$$

where $\sigma = (\theta^{-1})(\partial\theta/\partial Z)$ is the static stability, U the

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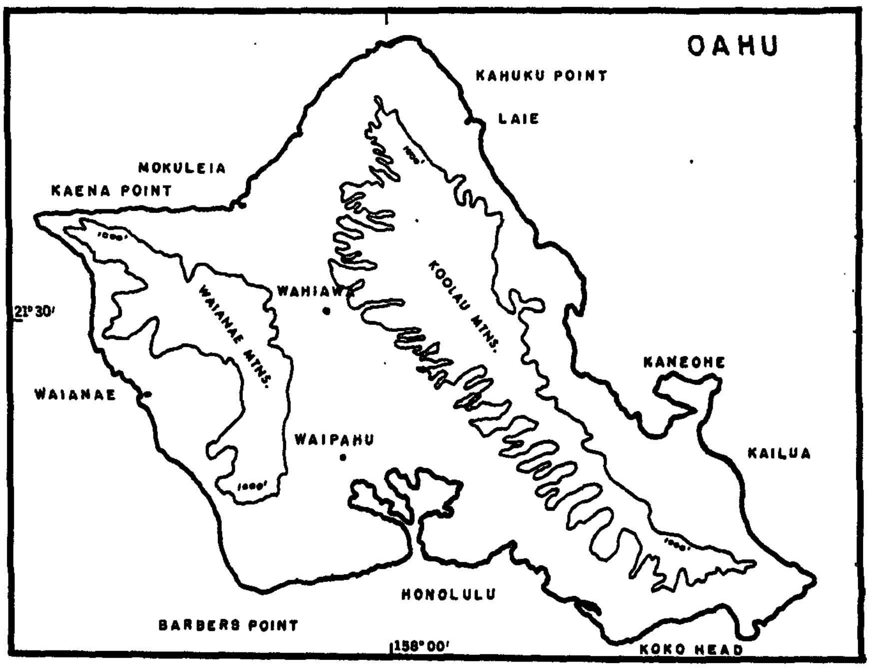

FIG. 1a. Island of Oahu, Hawaii.

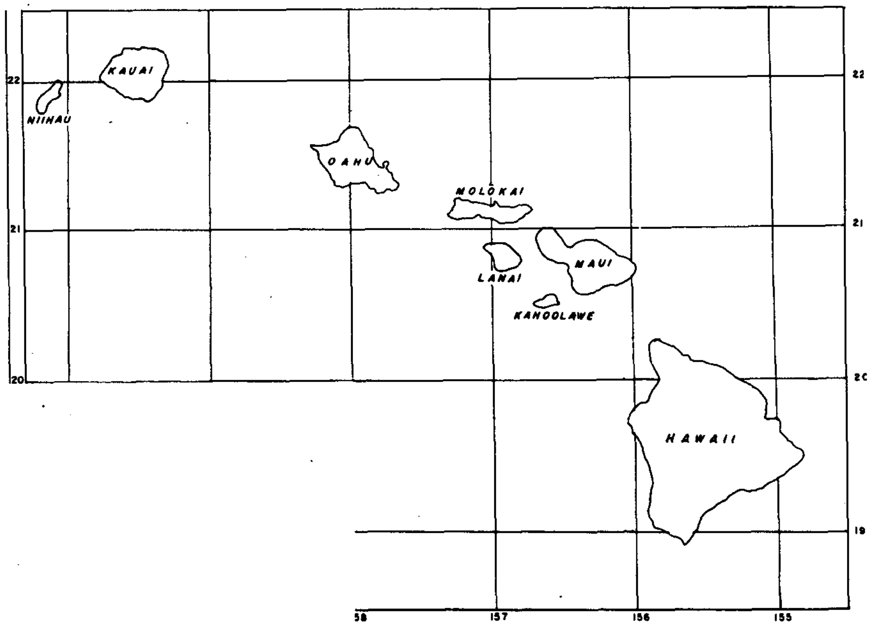

FIG. 1b. The eight main islands of the Hawaiian chain.

wind component normal to the mountain range, g gravity, and θ the potential temperature. The wavelength is inversely proportional to the square root of the Scorer parameter. This implies that short wavelengths occur with light winds and strong static stability, while long wavelengths occur with strong winds and weak static stability. During trade wind conditions (which occur 90% of the time from May to October and 50% of the time from October to May) where a strong temperature inversion is evident at $\sim$2000 m and where a wind maximum exists between the crest of the Koolaus and the inversion, short wavelengths predominate. During the winter especially, there may be southwesterly winds ahead of a deep trough and frontal system. Under these conditions little or no inversion is present; the wind increases continuously from the crest of the ridge to a maximum near the jet stream, and longer wavelengths predominate.

2. Discussion

a. Trade wind case

On 25 August 1977, an extraordinary example of trade wind lee wave development occurred. The trade inversion was somewhat higher than normal with its base at 2700 m. Strong ENE winds developed with the wind speed normal to the Koolaus increasing from 12 m s^{-1} near the crest of the range to a maximum of 18 m s^{-1} near 2100 m and decreasing to 13 m s^{-1} near the inversion. Figs. 2 and 3 are SMS-2 1 km visible imagery showing the development of wave clouds downstream from the Koolaus. In Fig. 2, taken at 1845 GMT (0845 HST), the first wave clouds can be seen forming across central Oahu. As a shower area to the northeast arrives over Oahu, the downstream development of wave clouds continues until the wave clouds extend 165 km downstream from the Koolaus and have a wavelength of 9 km (Fig. 3). The wave cloud pattern has a "herringbone" appearance with bending downwind at the outer edges. This may be due to confluence downstream of flow around the island of Oahu which has accelerated through the channels between the islands of Kauai and Oahu to the north and Oahu and Molokai to the south (Fig. 1).

b. Westerlies case

On 10 January 1977, an outstanding example of wave cloud formation in the reverse direction (west-southwest) occurred. In this case there was no inversion, but an isothermal layer was evident with its base at 1500 m. The wind component normal to the Koolaus increased from 12 m s^{-1} at the crest to 41 m s^{-1} at 13.7 km above the surface. In Fig. 4 the wave clouds are visible 250 km downstream and have a wavelength of 12 km. The wave clouds are not present over the entire distance because sufficient moisture is not present to produce the clouds.

c. Other areas of research

Several authors have demonstrated that a linear relationship exists between wavelength and the

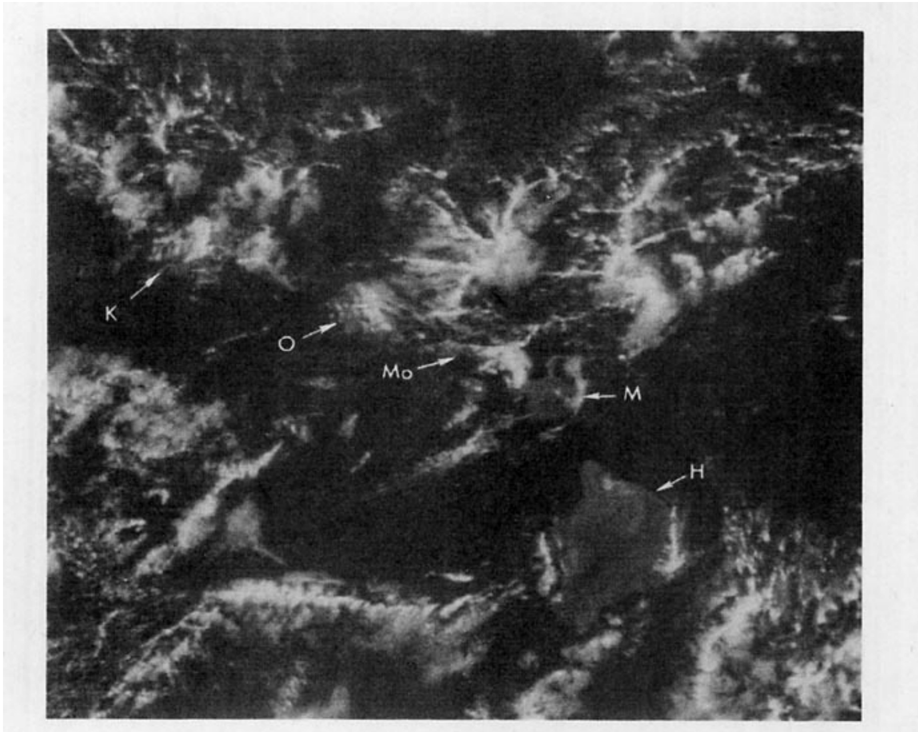

FIG. 2. SMS-2 1 km visible satellite imagery, 1845 GMT (0845 HST) 25 August 1977. K is Kauai, O Oahu, Mo Molokai, M Maui and H Hawaii Island.

mean wind speed through a deep layer of the troposphere (Corby, 1957; Alaka, 1960; Fritz, 1965). By noting that the first term in Eq. (1) accounts for 90% of the value of the Scorer parameter in most cases and that the static stability doesn't change very much except in the lower troposphere, the following formulation for wavelength λ can be derived (Alaka, 1960):

$$\lambda = 2\pi\bar{U}(g\bar{\sigma})^{-1/2}. \quad (2)$$

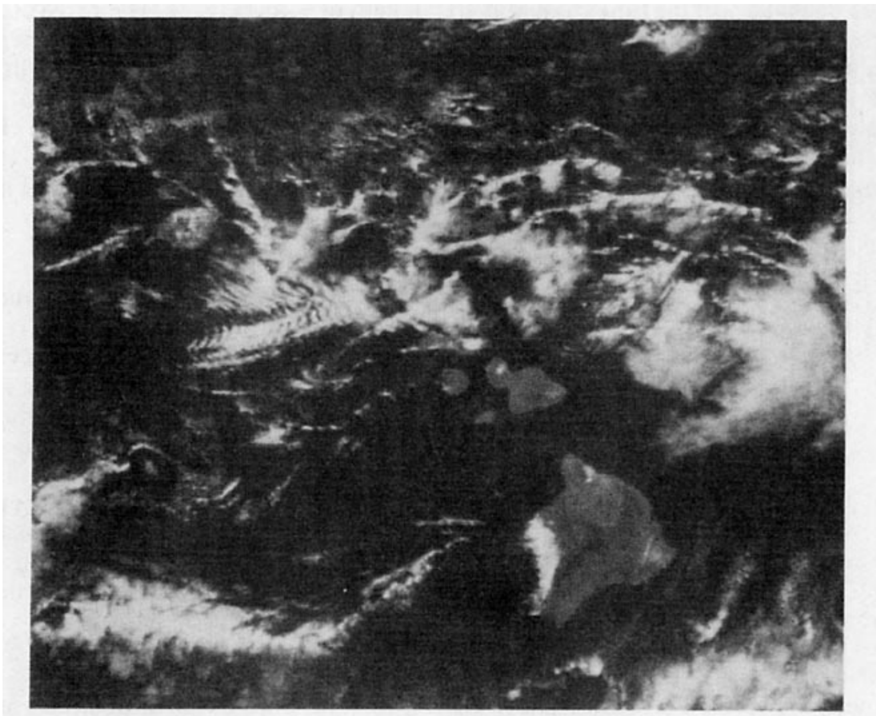

FIG. 3. SMS-2 1 km visible satellite imatery, 2145 GMT 25 August 1977.

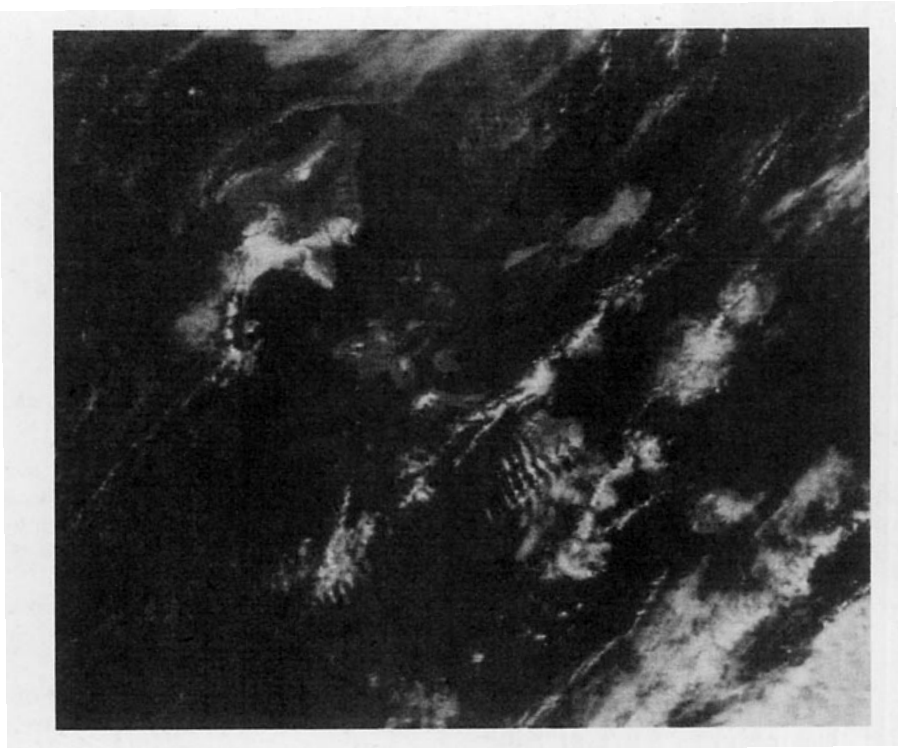

FIG. 4. SMS-2 1 km visible satellite imagery, 2349 GMT 10 January 1977.

Here the bar over U and σ indicates a mean value taken over a deep layer of the atmosphere. By applying Eq. (2) to Case a and taking averages of the static stability σ and wind speed U up to 250 mb, a wavelength of 6 km was calculated compared to a measured wavelength of 9 km. But by averaging σ and U from the crest of the Koolaus to the base of the temperature inversion, a wavelength of 7.2 km was calculated.

Operationally lee waves produce turbulence which affects aviation interests. In Case a, moderate turbulence was reported by a commercial jet on descent through the 1000 m level as it approached Honolulu International Airport. No documentation is available for Case b. Reiter and Foltz (1967) have formulated a relationship between gradient wind speed normal to the mountains and measured wavelength which gives the vertical motion in the lee waves, and they have empirically related this vertical motion to turbulence. With dry conditions in the atmosphere it is possible to have lee waves without having wave clouds visible in the satellite imagery. Under these circumstances Eq. (2) could be used as an input to the Reiter and Foltz equations. Corby (1957) has developed a regression equation for λ which gives acceptable results for cases associated with the westerlies. To achieve more acceptable results for trade wind cases, a similar correlation needs to be developed between the wavelength and the mean wind speed for the depth of atmosphere between the crest of the Koolaus and the trade inversion. Preliminary work has been done at the National Weather Service Forecast Office (WSFO) Honolulu to determine if Reiter and Foltz's equations can be used as an aid in issuing AIRMETS during lee wave events. As yet these equations can only be used when wave clouds are visible in the imagery, and nothing conclusive has been determined.

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