Trade Wind Rainfall atop Mount Waialeale, Kauai*

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ABSTRACT

Very large coast to mountain rainfall gradients have been observed in the trade winds and winter monsoons. Since the surface moist layer is usually capped by a subsidence inversion near 2 km, the rain is ‘‘warm.’’ On the top of a mountainous island, which is generally below the inversion, such as Kauai, trade wind rainfall can be very great and the coast to top rainfall gradient very large. Autographic rainfall measurements at the top of Mount Waialeale (1598 m MSL, one of the wettest spots on the earth) on Kauai together with surface and upper-air measurements made at Lihue, 20 km to the southeast, and weather satellite images confirm and expand on earlier descriptions of the nature of mountain rainfall in the trade winds.

Significant rain results from moderate or fresh trade winds being lifted up the eastern escarpment of Waialeale, but only when a band or area of cumulus extends upwind of the mountain. Small wind shear in the vertical and a sharp upper limit to the moist layer reduce entrainment and facilitate growth of cloud droplets. At the mountaintop rain is usually light or moderate, with drops smaller than 2 mm, but persisting long enough to produce large accumulations. Along the windward coast, drops usually evaporate before reaching the ground. Divergence and upward motion east of an upper-tropospheric trough barely affect the moist trade wind layer. Cloud lines associated with shear line extensions of cold fronts or with dying tropical cyclones to the south account for much of the rain though short-lived mesoscale cloud systems are also important.

Thunderstorms are very rare with surface flow from a trade wind direction. The wind then curves cyclonically on the northwest sides of sharp troughs or small cyclones. Upper-tropospheric southwesterlies usually prevail. The nocturnal rainfall maximum at Waialeale probably stems largely from radiational cooling at the top of the moist layer causing clouds over and upwind of the island to increase. Other trade wind islands of about the same size and height as Kauai, but with no mountaintop rain gauges, probably also have large coast to mountaintop rainfall gradients.

1. Introduction

In the trade winds, very large rainfalls and rainfall gradients have been observed in the windward mountains of Central America, Hawaii, and Mauritius. The winter monsoon produces similar rains on the east coast mountains of the Philippines and Vietnam. A subsidence inversion generally limits cloud tops to about 2 km. Thus almost all the rain falls from warm clouds.

Over the Hawaiian Islands winter trade winds blow 50% of the time, and the subsidence inversion, which is typical of the trade winds, occasionally disappears. In summer, trade winds and the inversion prevail on more than 90% of days (Sanderson 1993). Charts of Hawaiian summer rainfall (Giambelluca et al. 1986) reveal two distinct mountain regimes.

1) Where the mountaintops generally penetrate the trade wind inversion, in east Maui and the island of Hawaii, rainfall maxima lie near 1-km MSL and are only about twice as large as rainfall along the windward coast. There have been several field experiments on the island of Hawaii—Project Shower (1954), the Warm Rain Project (1965), Project Ahupua’a (1978), the Joint Hawaii Warm Rain Project (1985), and the Hawaiian Rainband Project (1990). The coastal rains have a strong diurnal cycle with nocturnal maxima due to interaction between trade winds and nocturnal drainage flows (Leopold 1949). A contrary hypothesis, advanced by Smolarkiewicz et al. (1988), interpreted trade wind interactions with high islands (Hawaii) in terms of low Froude number

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(about 0.2) flow past an obstacle. This would cause a shock (bow wave) to develop and flow along the mountain slope to reverse. The rainbands often observed in Hilo Bay were thought to be due to this mechanism. The Hawaiian Rainband Project (HaRP), which tested this hypothesis, included 50 automated mesonet stations, rawinsondes, tethersondes, a low-level wind profiler, two Doppler radars, and a research aircraft, and provided data for a series of papers on the interactions of surface temperature, airflow and rainfall and their diurnal variations. Apparently, both thermal effects (Leopold's view) and dynamic effects (Smolarkiewicz et al. 1988) are present, though the former seem to dominate on shore (Chen and Wang 1994; Carbone et al. 1998).

2) By contrast, where the mountaintops lie below the trade wind inversion, in Kauai, west Maui, and Oahu, phenomenally large rainfall maxima lie near the tops and are 10–16 times as large as rainfall along the windward coasts. This study, focusing on Kauai, uses autographic rainfall records from Mount Waialeale, rawinsonde data from Lihue, and satellite images.

In what follows, previous work is described, the geography of Kauai and in particular of Mount Waialeale is outlined, statistical relationships among Waialeale rainfall and elements measured at Lihue are evaluated, and the character of Waialeale rainfall determined. Then come discussions of synoptic influences, thunderstorms, and diurnal variation. Local time (LT) is used. In Hawaii this is the same as Hawaii standard time (= UTC − 10).

2. Previous studies of Hawaiian trade wind rainfall

Lyons (1982) showed that the dominant eigenvector of Hawaiian summer rainfall accounted for 58% of the variance and was unequivocally related to trade wind orographic effects. However, Lyons found that at Lihue (Fig. 1) monthly trade wind speed is only weakly correlated to monthly trade wind rainfall ($r = 0.30$ for summer).

Larson (1978) used GOES images to classify the Hawaiian summer rainfall of 1976 and 1977. Statewide dryness was not uncommon. Then, satellite images showed little cloud upstream or ''pancake'' stratocumulus beneath a strong inversion near 1500 m MSL. On the other hand, if one island experienced ''wet'' trades, the other islands would usually be dry. Various types of cloud lines or zones extending upwind of or across an island accounted for all of the wet days.

Woodcock (1975) described rainfall on a section perpendicular to the Koolau Range on Oahu (highest point 946 m MSL) during periods of ''anomalous orographic rains.'' These accompanied northeasterly surface winds, which set in behind a cool season cold front. At mountain stations prolonged continuous rain averaged more than 50 mm a day, more than 10 times as much as at coastal windward stations. In the satellite images a cloud deck extended 100–800 km northeast of Oahu.

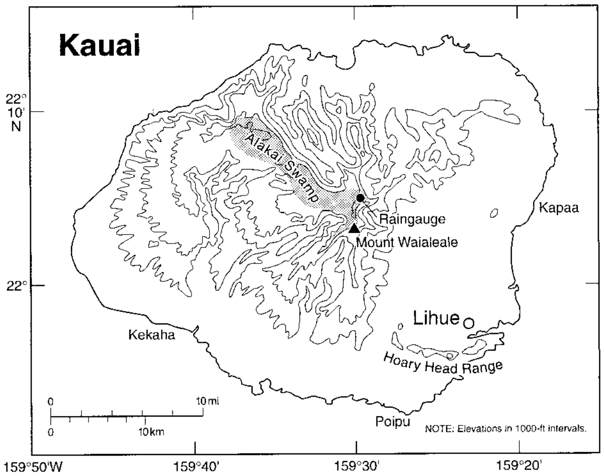

FIG. 1. Island of Kauai, showing location of Mount Waialeale recording rain gauge and Lihue Airport.

In an earlier study of the same area, Mordy and Eber (1954) found that mountain stations recorded appreciable rain if the range were covered by stratiform clouds whose tops did not exceed 2600 m MSL and if well-developed cumulus were coming from over the sea. They noted that ''the incoming trade clouds do not need to be raining while still at sea in order to produce significant rain when crossing the mountain ridge. . . .''

These findings suggest that upwind low cloud is prerequisite for significant trade wind rain, and that at these times mountain rainfall greatly exceeds coastal rainfall.

3. Geography of Kauai

Kauai, northernmost of the large islands in the Hawaiian chain (Fig. 1), is a deeply eroded extinct volcano (Mount Waialeale). The original caldera has been almost filled with lava. The Alakai Swamp covers the mountaintop, which slopes gently toward the northwest from the highest point (1598 m MSL). After the major eruptions ended several million years ago, the eastern flank of the shield collapsed to form what is known as the Lihue basin (MacDonald and Abbott 1970). Lihue Airport, a first-order meteorological station, lies on the coast, 20 km southeast of the mountaintop.

4. Data

On Mount Waialeale, a few meters back from the edge of the cliff bordering the Lihue basin, the U.S. Geological Survey set up a rainfall station in 1912 at 1547 m MSL; since 1949, a recording rain gauge has been operated there. The gauge is serviced by helicopter at 2–3-month intervals, weather permitting, and has provided a discontinuous record.

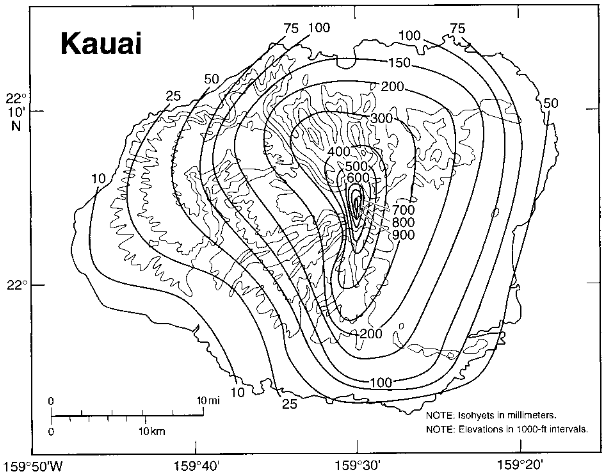

FIG. 2. August median rainfall (mm) in Kauai for approximately 60 yr of data [from Giambelluca et al. (1986)].

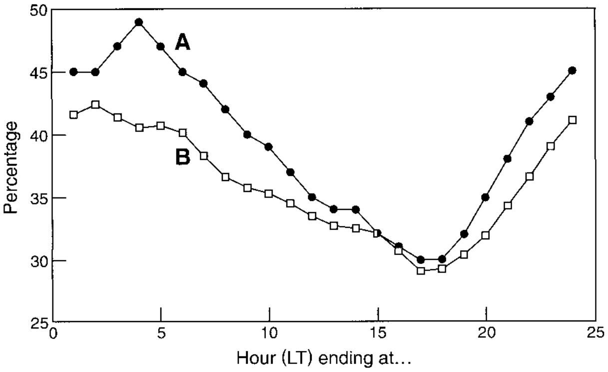

FIG. 3. Smoothed diurnal variation of rainfall frequency at Mount Waialeale: curve A for 351 trade wind days in 1976 and 1982 and curve B for Jun, Jul, Aug, and Sep, 1972–1993. Each smoothed value, $f_s = (f_{-1} + 2f + f_{+1})/4$.

The median annual rainfall on Mount Waialeale, 11 415 mm, makes it one of the wettest spots on the earth and accounts for the mountaintop swamp. Too much water and too little sun at the top stunt rain forest flora, which flourishes farther down the mountain. During winter, when cyclonic circulations often interrupt the trade winds, and the trade wind inversion may disappear, Waialeale is seven times as wet as Lihue. During summer, trade winds and their inversion prevail, and storms are rare; Lihue is much drier than in winter, and because Waialeale rainfall stays at the winter level the ratio increases to 14–1 in August (Fig. 2).

Two trade wind periods were studied. Between 1 May and 31 December, Waialeale rain gauge, Lihue rawinsonde and surface observations, and weather satellite images were analyzed for 197 days in 1976 and for 154 days in 1982. Only those days with resultant surface wind direction at Lihue between north and east were selected. At Waialeale the 1976 period was dry with median daily rainfall 11 mm and 1982 was wet with median daily rainfall 23 mm. Corresponding values at Lihue were 0.3 and 0.5 mm.

Figure 3 confirms that these typified all trade wind days. It shows the diurnal variation of rainfall for the study period and for the long term for the predominantly trade wind months of June, July, August, and September. The curves are in phase. The smaller amplitude for the long term resulted from admixture of non–trade wind days.

Twice-daily rawinsoundings were made at 0000 UCT (1400 LT) and 1200 UCT (0200 LT). Daily (LT) pressure (mb) of the base of the dry layer (top of the moist layer and the level of minimum dew point depression) were calculated using the expression

$$P_{\text{Daily}} = (P_{02\text{LT}} \times 8 + P_{14\text{LT}} \times 12 + P_{02\text{LT Next day}} \times 4)/24.$$

5. Statistical relationships

Although rainfall data are notoriously noisy, correlation among Waialeale daily rainfall and other variables measured at Lihue throw light on causes of the rain and on trade wind interrelationships. The years 1976 and 1982 were separately analyzed (Table 1). For a sample size (n) of 197 (1976), the simple correlation coefficient $r \geq 0.18$ and for $n = 154$ (1982), $r \geq 0.21$, r is significant at the 1% level. For any pair of variables, significant same-sign correlations for the two quite different years (shown in boldface), strongly suggest a physical relationship between the variables. Waialeale rain-

TABLE 1. Correlations among daily values of Waialeale rainfall (WR) and the following variables measured at Lihue for trade wind days in 1976 (first value) and 1982 (second value)—rainfall (LR), trade wind strength (TS), total cloudiness (TC), depth of the surface moist layer (MLD), surface dewpoint depression(DPD), surface pressure (P_S), and wind direction (DD) at 200 mb. Correlations with the same sign and significant at the 1% level are shown in bold face.

	Lihue						
	(LR)	(TS)	(TC)	(MLD)	(DPD)	(P_S)	(DD)
(WR)	**0.51/0.34**	**0.34/0.31**	**0.46/0.45**	**0.40/0.43**	**−0.29/−0.36**	0.16/0.01	−0.09/−0.0
(LR)		0.06/−0.12	**0.32/0.35**	**0.29/0.46**	**−0.34/−0.54**	−0.07/−0.20	−0.02/0.10
(TS)			**0.33/0.11**	0.04/−0.07	**0.42/0.32**	**0.52/0.38**	−0.09/0.16
(TC)				0.14/0.44	−0.02/−0.52	0.21/−0.07	−0.19/−0.14
(MLD)					**−0.30/−0.51**	0.06/0.28	0.02/0.09
(DPD)						0.22/0.14	−0.06/0.17
(P_S)							−0.05/0.19

fall is linked positively with Lihue rainfall and Lihue cloudiness. Published climatological data for Lihue include only total cloudiness (sky cover), whereas the work already quoted links low-cloud amount to mountain rainfall. At least for 1976 and 1982, low-cloud amount and total cloud amount are highly correlated and both are equally correlated to Waialeale rainfall. Hence, total cloudiness is a suitable proxy for low-cloud amount.

a. Trade wind strength

Trade wind strength is linked positively to Waialeale rainfall, reflecting orographic uplift. That the correlation is smaller than expected, stems from the fact that although >50 mm fell on 26 days of fresh trade winds, <6 mm fell on 17 other fresh trade wind days. As Siler (1962) said, ''but topography alone is not the rain producing mechanism for it has been observed many times that surface trades of approximately equal strength and direction do not produce rainfall totals of anywhere similar magnitudes.'' Cloudiness is the differentiator. In the 26 wet days, cloudiness always exceeded 70%, while in the 17 dry days it was always less than 70%. This confirms the essential role of upwind cloudiness in the production of significant rain.

That trade wind strength and Lihue rainfall are unrelated [confirming Lyons's (1982) findings for monthly values] suggests that lifting up the mountainside does not extend to the coast, and that Lihue cloudiness is representative of cloudiness over the open ocean to windward.

Trade wind strength is unrelated to moist layer depth, and is positively related to surface dewpoint depression, attesting to the importance of turbulent mixing of dry air downward through the top of the moist layer (see Riehl 1979). This overcomes a decrease in dewpoint depression caused by stronger winds increasing evaporation from the sea, combined with an oceanic mixed layer deeper than 50 m that ensures near-constant surface air temperature.

b. Moist layer depth

The deeper the moist layer, the less downward mixing of dry air affects surface conditions, thus the negative correlation with surface dewpoint depression. The resulting deeper cloud gives more rain at both Waialeale and Lihue. None of the relationships of Table 1 suggest a cause for changes in moist layer depth.

Table 1 reveals an apparent inconsistency; Waialeale rainfall is positively linked to trade wind strength and negatively linked to surface dewpoint depression, which, in turn, is positively linked to trade wind strength. This can be so if orographic enhancement of Waialeale rainfall occurs only under cloudy skies. Otherwise, increased trade winds, by increasing surface dewpoint depression could reduce cloud depth. In other words, cloudiness and trade wind strength independently contribute to Waialeale rainfall. A multiple regression equation incorporating both variables and moist layer depth gave $r = 0.64$ for 1976 data. The same equation applied to 1982 gave $r = 0.59$. This strongly suggests that dry year rainfall controls also apply in a wet year and presumably in any year.

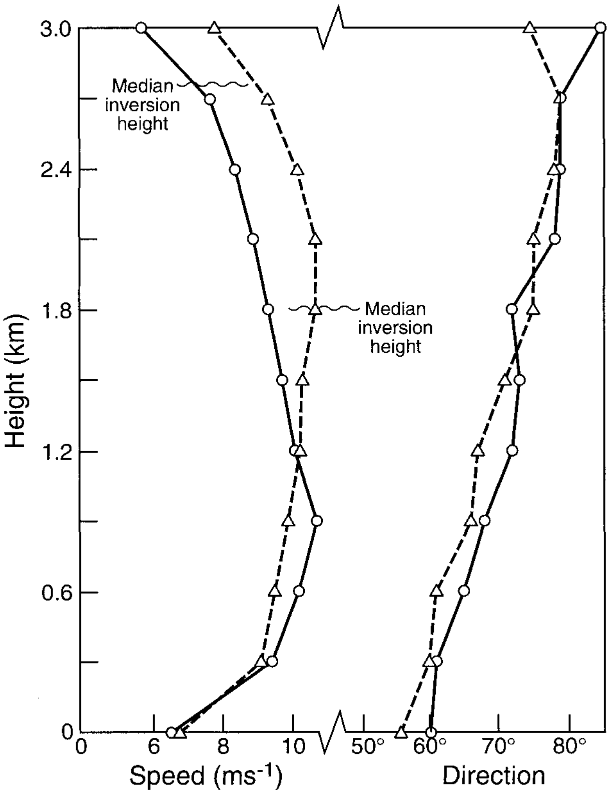

FIG. 4. Resultant winds at Lihue during fresh trade winds. For 12 wet days (>50 mm, full lines) and 16 dry days (<6 mm, dot–dashed lines) at Waialeale.

Surface pressure is significantly related only to trade wind strength, confirming what is known of subtropical and winter monsoon anticyclones. Pressure near the equator remains almost constant; thus when an anticyclone intensifies, pressure rises and pressure gradients increase equatorward of the center, that is, in the trade winds.

6. The character of Waialeale rain

As Larson (1978) observed, as the correlation suggest, and as satellite images confirm, wet days differ greatly from dry days in the character of low clouds near Kauai. On wet days, lines or masses of trade wind cumulus extend upwind of the island, whereas on dry days either the moist layer top is found near the mountain peak, or skies are almost clear upwind.

Whether Waialeale is wet or dry, the trade winds blow roughly along the shear (Fig. 4), and as elsewhere, trade

TABLE 2. Observations and thermodynamic elements for the wet and dry Waialeale days of Fig. 4.

	Waialeale wet days		Waialeale dry days	
	Range	Median	Range	Median
Waialeale rainfall (mm)	51–140	67	0–6	4
Lihue rainfall (mm)	0–25	2	0–3	0
Lihue LFC (mb)	629–950	884	303–1012	914
Lihue CAPE ($m^2\ s^{-2}$)	8–1298	174	0–1300	54

wind cloud lines in the Hawaiian region usually parallel the winds (Malkus 1963). On dry (wet) days the inversion is about 200 m below (600 m above) its normal level. The average wind speed profile for wet days shows a maximum near 1 km. Takahashi (1977b) observed a similar profile with trade wind cloud bands lying almost parallel to the wind, an association that is theoretically supported by Brown (1970). The profile resembles the normal for over-ocean trade winds (Riehl et al. 1951). Lack of a maximum below the inversion in the dry days average (see also LeMone and Pennell 1976) seems to confirm that a bowed wind profile necessarily accompanies a cloud line.

Lihue radiosonde data for the wet and dry Waialeale days of Fig. 4 were analyzed (Table 2). For both the level of free convection (LFC) and the convective available potential energy (CAPE) the range for the wet days included 87% of the values for the dry days. These small wet–dry differences may stem from the fact that even on the wet days Lihue generally experienced little rain. LFC and CAPE are not obviously related to cloudiness upstream from Kauai.

Persistent cloud lines would need to coincide with low-level convergence of about $5 \times 10^{-5}\ s^{-1}$ (LeMone and Pennell 1976). To the rise resulting from the convergence would be added mechanical lifting up the windward face of Waialeale, estimated to be an order of magnitude larger, and the same for both the wet and dry days of Fig. 4. Thus, convergence into a cloud line, by contributing insignificantly to the total vertical motion, cannot solely account for the differences between wet and dry days at Waialeale when fresh trade winds are blowing.

Mordy and Eber (1954) and Woodcock (1975) foreshadowed the explanation (see section 2). Figure 4 suggests, and we hypothesize, that in a cloud line extending upwind from Kauai and about 1500 m deep, cloud droplet motion is constrained in the horizontal, since the cloud line is oriented parallel to both the wind and the wind shear, and in the vertical by the trade wind inversion or stable layer. Thus entrainment drying is reduced and 1-mm drops are commonly observed near the cloud tops (T. Takahashi 1979, personal communication). Over the ocean and along the coast, where drops falling out of the cloud mostly evaporate, rainfall is slight. The huge rainfall gradient between coast and mountaintop may stem from a combination of causes. The mountain forces the cloudy air to rise and possibly deepen, and increases the supply of moist surface air. Enhanced condensation and collision frequency would accelerate drop growth. At the mountaintop, well within the cloud, there is no evaporation; mechanical uplift suddenly stops and the resulting ‘‘mini-cloudburst’’ could further enhance rainfall.

On the wet days of Fig. 4, 50% of the total rainfall was accounted for by hourly rates ranging from 3 to 7 mm. For these rates Blanchard (1953) collected no drops larger than 1.5 mm at the base of orographic trade wind clouds on the island of Hawaii. Mordy and Eber (1954) measured maximum drop sizes from 1 to 2 mm just leeward of the crest of the Koolau Range on Oahu. For all trade wind hours with rain at Waialeale during the 351 days of 1976 and 1982, amounts were less than 7 mm 90% of the time accounting for 64% of the total rainfall. Winner (1968) confirms that this preponderance of light rain is unusual in the Tropics. He empirically determined a relationship between annual rainfalls and the frequency of hourly amounts for stations in the Panama Canal Zone and confirmed the results for stations in Thailand and Cambodia. Applying his equations for hourly rainfalls of 1 mm or more to Waialeale gives an hourly frequency of less than half of the observed frequency.

Although the drops are not large, great numbers could not possibly develop in the 40 min it takes an air parcel to move from the coast to the Waialeale station, were the parcel cloud free as it crossed the coast (Takahashi 1973). Thus, clouds upwind are prerequisite to significant rain on Waialeale.

Moist-layer depth is positively related to Waialeale and Lihue rainfalls. Changes in moist layer depth stem from ‘‘strong synoptic variations . . . and presumably its large small-scale variability’’ (Riehl 1979). In this sense, convergence along a cloud line probably increases moist layer depth, in a process analogous to that observed along the near-equatorial trade wind convergence zones (Ramage et al. 1981). During trade wind days with periods of continuous rain at Waialeale, the moist layer was 500 m deeper than on all trade wind days for 1976 and 1982. Perhaps too, in moderate or fresh trade winds, lifting along the slopes of Waialeale could raise the top of the moist layer after it is measured at Lihue.

7. Case study, 13–17 October 1976

It was documented that 186 mm of rain fell continuously at Waialeale in the 36 h between 0000 LT on 14 October and 1200 LT on 15 October. The extreme uniformity of the rain (Fig. 5) is typical of other prolonged events and shows no evidence of convective interruptions. There were no thunderstorms. Apart from one hourly fall of 14 mm, the rates are those expected from orographic trade wind clouds (Fig. 6; Blanchard 1953).

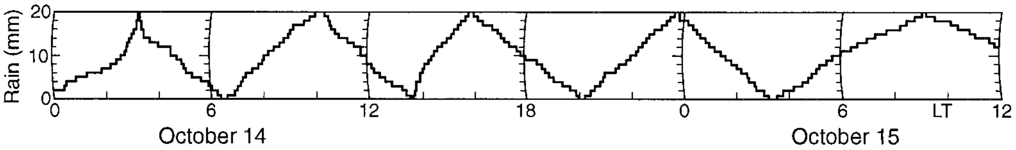

FIG. 5. Waialeale pluviogram for 14 and 15 Oct 1976. Tipping bucket activates recorder at 1-mm increments.

a. Upper troposphere

A northeast–southwest-oriented trough, which lay west of Kauai on 13 October, moved eastward north of 30°N and remained stationary south of 30°N. On 14 October the two segments parted; between them a ridge lay across the Hawaiian islands (Fig. 7). Cirrus clearly marked the southern edge of the jet stream north of Kauai. Location of the jet stream and divergence over Kauai duplicated conditions found by Hill (1964) to favor rising motion in the upper troposphere decoupled from subsidence in the lower troposphere. Beginning on 14 October, the trough to the west intensified and moved east, crossing Lihue late on 16 October. The upper trough generated a midtropospheric moist layer to its east, accompanied by a middle cloud overcast.

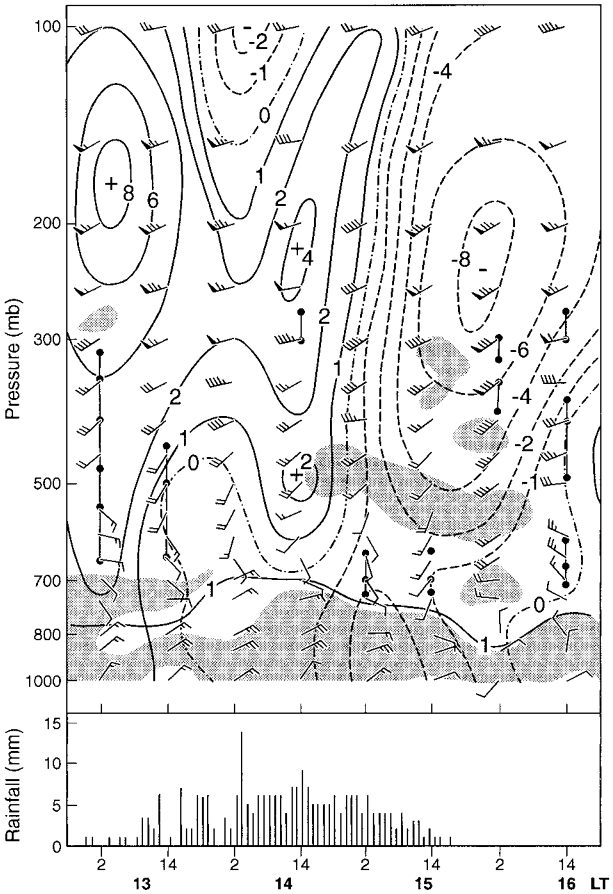

FIG. 6. Time cross section for Lihue (upper air) and Waialeale (rainfall) for 13–16 Oct 1976. Pressure height change isopleths (decameters) refer to midpoints of the appropriate 24-h intervals. Layers with relative humidity >70% stippled. Layers with relative humidity <20% shown with vertical line segments at top of wind arrows.

b. Lower troposphere

Low clouds upwind from Kauai became organized into a band by 14 October At 0000 LT, this cloud had expanded and spread across Kauai from the north (Fig. 8). Continuous rain set in at Waialeale, associated with moderate trade winds. Rain ceased on 15 October, as winds slackened with arrival of a col between two high cells. At the same time, the cloud mass moved clear of Kauai.

Throughout the rain period, a dry layer was sandwiched between the trade wind moist layer and a middle tropospheric moist layer (Fig. 9). Some of the rain falling from the latter would have reached the former, since Lihue recorded 20 mm. The upper moist layer was deepest at 0200 LT on 16 October. At this time, surface winds were light, the low cloud mass had shifted from Kauai and Waialeale was dry, so any rain coming from the upper layer evaporated before reaching the surface.

8. Possible synoptic influences

Daily rainfalls exceeding 50 mm may occur at Waialeale during trade winds, when the moist layer is deep

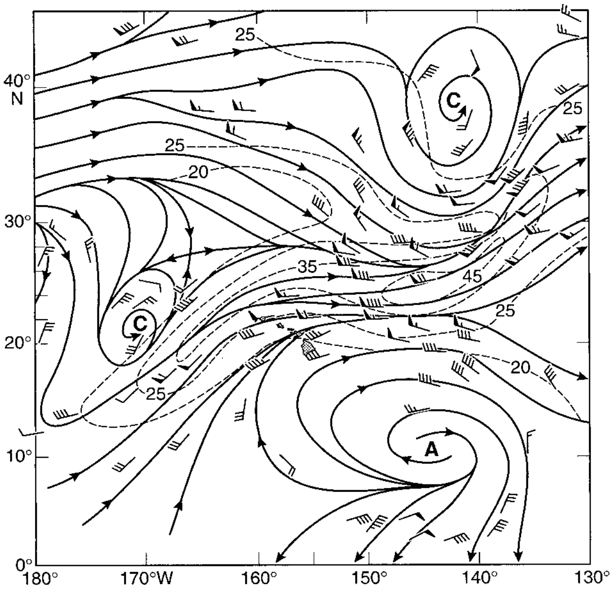

FIG. 7. Kinematic analysis of 250 mb winds for 1400 LT 14 Oct 1976. Isotachs (dashed) are labeled in m s^{-1}.

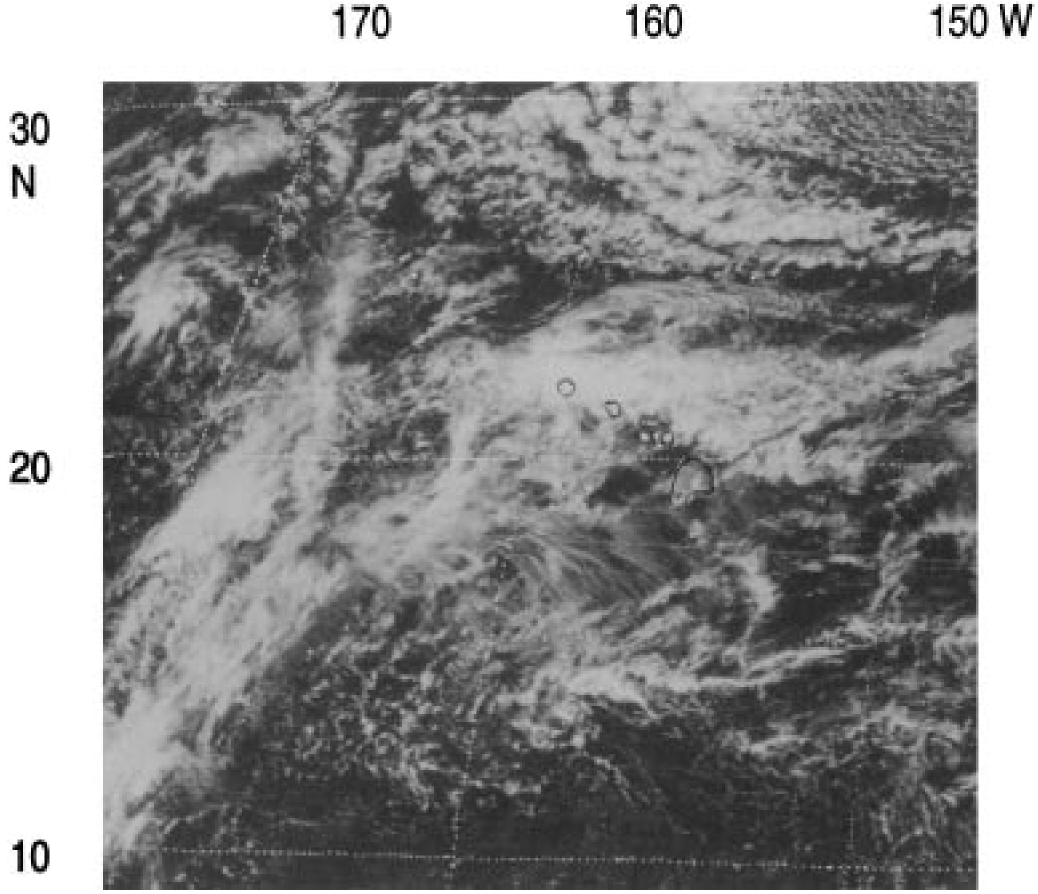

FIG. 8. GOES image (visible spectrum) of clouds in the area of Hawaii for 1415 LT 14 Oct 1976.

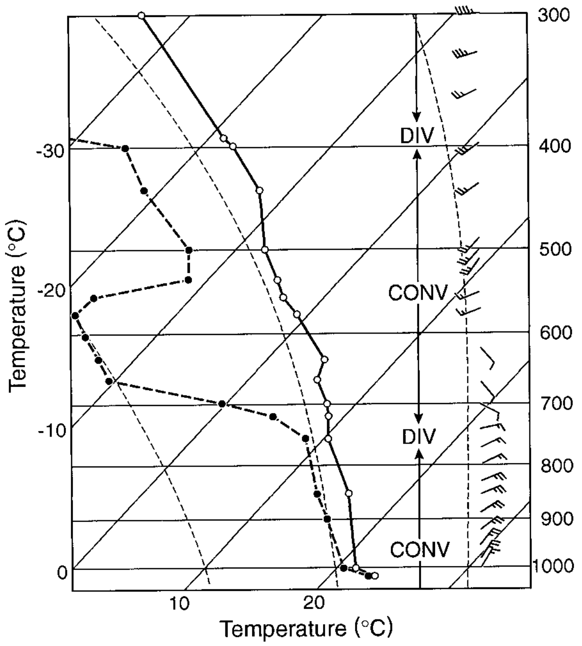

FIG. 9. Lihue rawinsounding for 1400 LT 14 Oct 1976. Full line temperature, dashed line dewpoint.

enough and clouds extend upwind of Kauai. Does the synoptic scale determine whether these preconditions are satisfied? Conventional wisdom calls for rising motion and unsettled weather beneath 200-mb southwesterlies east of an upper-level trough. Worthley (1968), studying the impact of upper-tropospheric cyclones on Hawaiian rainfall patterns, found that orographic effects masked any cyclonic effects and that heavy rain, when it did fall, was most likely in the northeastern and western sectors of the cyclone, and least likely in the southeastern sector. In a study of 300-mb troughs, Han-Shun-Cheong (1970) concluded that for northern (windward) Oahu daily rainfall >2.5 mm is more likely with the trough near to or west of the island than in other locations. However, the probability is $<40\%$, while the average trough-day rainfall (3.8 mm) is not much more than average nontrough-day rainfall.

These inconclusive results are supported in Table 1. Apart from a slight negative correlation between wind direction at 200 mb and total cloud amount at Lihue (more middle cloud with winds with a southerly component), the table shows no link to any other variable, even to moist layer depth. Also, in the case study, Waialeale rain diminished to zero while the upper trough still lay to the west (Fig. 6). In the trade winds, the dry stable air above the top of the moist layer hinders vertical motion almost effectively as the surface of the earth. Upper-tropospheric divergence usually found east of a trough in the westerlies, may cause cloud to form in the middle or upper troposphere; compensating convergence occurs beneath in the dry layer, and the moist layer remains undisturbed (Fig. 9), although according to Takahashi (1977a), if drizzle fell from the upper into the lower layer, it would significantly accelerate the precipitation process. Thus Waialeale rainfall could sometimes be slightly affected.

Over Kauai, a disturbed upper troposphere and trade winds are ‘‘decoupled’’ on about 20% of days. On 75% of these days, the intervening dry layer is between 4 and 6 km deep. Decoupling was reported even more frequently in other trade wind and winter monsoon regions (Seck 1962; Hill 1964; Fox 1969; Southern et al. 1970; Kloessel and Albrecht 1989). In all cases, low-level flow was anticyclonic. Causes of a midtropospheric moist layer are often hidden, although usually upper-tropospheric flow from west and toward the pole is present.

The most persistent cloud lines accompany the following:

1) Wind shear lines extending southwest from middle latitude cold fronts. Light trade winds freshen at the shear line, which moves rather slowly southeastward.
2) Dissipating tropical cyclones moving westward less than 750 km to the south of Kauai. Remnant spiral rainbands cross Kauai. On 14 such days between 1972 and 1993, when Waialeale rainfall was measured, prolonged light or moderate rain fell with a median of 109 mm. Lihue rainfall was insignificant (median 2 mm).

Other cloud lines are usually more brief, and too small to be detected in the synoptic observing network. Within low cloud-filled and otherwise uniform trades, mesoscale cyclones have sometimes been observed, usually associated with shear lines (Ramage et al. 1981; Raymond and Lewis 1995). The clouds may be deep and thundery (see below). Little is known of their life cycles.

9. Thunderstorms

At Lihue, between 1954 and 1996, the annual average of eight days of thunderstorms included three during which the resultant surface wind was from the trade wind direction. During these thunderstorms, the midtropospheric dry layer was absent. Of the 351 trade wind days of 1976 and 1982 studied in detail, only two experienced thunderstorms at Lihue. On 1 and 2 August 1982 thunderstorms accompanied passage of rainbands that extended north from a dying tropical cyclone (Gilma) moving west-northwest 350 km to the south of Kauai. The winds curved cyclonically over the island, and 319 mm of rain fell on Waialeale.

On 40 trade wind days between 1972 and 1993, rainfall was measured at Waialeale, and Lihue reported thunderstorms. On every occasion, surface winds curved cyclonically, either in rainbands extending north from a tropical cyclone, or just northwest of a sharp trough or depression, or in a col between anticyclonic cells. The median wind direction at 200 mb, 252° compared to 278° for the 1976 and 1982 trade wind days, suggests that on rare occasions, upper-tropospheric divergence may induce rising motion in the normally subsiding trade winds. Tropical squall lines caused most of the thunderstorms. Several investigators have described these lines (e.g., Zipser 1977). Barnes and Sieckman (1984) found that in GATE thunderstorms, wind shear relative to the squall line averaged 11 m s^{-1} between 1 and 3 km. Slow-moving cloud lines showed little or no shear, comparable to the shear for rainy trade wind days shown in Fig. 4.

Waialeale median rainfall, 98 mm, was only five times the Lihue median, indicating weakened orographic enhancement. On three days, with land and sea breezes, the sea breeze contributed to afternoon rain at Waialeale. At the same time a thunderstorm was reported at Lihue, although no rain fell there (see l0 c).

Although surface cyclonic flow is a prerequisite for thunderstorms it is not sufficient, since it was not always accompanied by thunderstorms.

10. Diurnal variation

Surface dewpoint depression at Lihue varies diurnally (afternoon minus early morning) by 3.7°C, equivalent to a change in lifting condensation level of about 450 m. This influences the diurnal variation of cloudiness there, the nocturnal maximum exceeds the afternoon minimum by 40%, and should favor the diurnal variation of rainfall. However, since dewpoint stays almost constant through the day over the ocean, this process does not affect the upwind cloudiness, which is so important to Waialeale rainfall.

Over the open ocean, trade wind cloudiness is greatest near 0800 LT and least near 1600 LT, with a range of 14% (Brill and Albrecht 1982). They concluded that diurnal variation of heating and cooling at the top of the moist layer, by moving the top of the layer up during the night and down during the afternoon, contributes most to the variation in cloud depth and consequently to cloudiness. At Lihue, during 1976, the median height of the top of the moist layer at 0200 LT was about 50 m greater than the median height at 1400 LT, in agreement with Brill and Albrecht; but there was no difference in 1982. This process, though in the right sense, inadequately accounts for the diurnal variation in rainfall.

Starting in late afternoon on most trade wind days, satellite images show a significant increase in low clouds over the ocean that probably resulted from cooling of the top of the moist layer. This was already close to

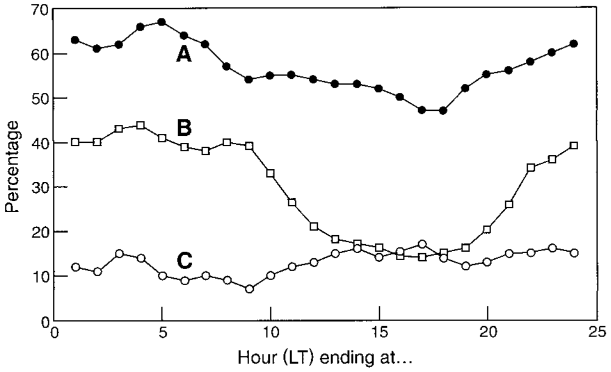

FIG. 10. Smoothed diurnal variation of rainfall frequency at Mount Waialeale for three categories of trade wind days during 1976 and 1982. (A) Days with low cloud over and upwind of Kauai (n = 164). (B) Undisturbed trade wind days (n = 117). (C) Days with land and sea breezes over Kauai (n = 70).

saturation and with cooling tending to be concentrated there, clouds that had been scattered in the afternoon often increased to become broken and later overcast, thus creating conditions favoring enhanced droplet growth upwind of the mountain. Doppler radar and satellite images in the trade winds over the east coast and upwind of the island of Hawaii revealed a similar diurnal variation in radar intensity and cloud cover, which Austin et al. (1996) and Carbone et al. (1998) attributed to radiative forcing. Betts et al. (1995) came to the same conclusions for North Atlantic stratocumulus. This process probably makes the largest contribution to the diurnal variation of rainfall at Waialeale.

Figure 3 shows the diurnal variation of rain frequency by hourly intervals for the trade wind days of 1976 and 1982 (n = 351, total rainfall 9687 mm). The broad nocturnal maximum is about 50% greater than the afternoon minimum. However, as Fig. 6 suggests, rain from a cloud line effectively masks any diurnal variation. When trade winds are light, land/sea breeze circulations might prevail. Figure 10 shows three distinct diurnal regimes.

1) Diurnal variation on days with upwind cloud (n = 164, total rainfall 7728 mm).

   The nocturnal maximum is less than 40% greater than the afternoon minimum, while the average daily rainfall of 47 mm compares to 28 mm for all days. No diurnal variation in frequency of cloud lines could be found. Even so, the nocturnal maximum/afternoon rain frequency minimum persisted, though muted.
2) Diurnal variation on days of undisturbed trade winds (n = 117, total rainfall 1414 mm).

   Daily rainfall averages 12 mm and is about three times more likely at night than in the afternoon due to the absence of organized cloud systems.
3) Diurnal variation on days with a land/sea breeze regime (n = 70, total rainfall 545 mm).

   These are the driest days, averaging 8 mm. Downslope motion at night, and light trade winds and little orographic lifting during the day are responsible. Convective clouds accounted for a slight afternoon/evening maximum. During four 2-hourly periods on four afternoons, 127 mm fell. The moist layer was then deep enough (>2600 m) to allow significant mountain convection. The coast of Kauai lay in an annular clear zone beneath the descending branch of the sea breeze circulation and Lihue was dry.

During light trade winds, the Froude number for Kauai is low enough for a shock wave to develop upstream. However, any effect on Waialeale rainfall is masked by the enhanced diurnal temperature cycle and development of land and sea breezes.

11. Conclusions

1) Over Kauai, during moderate or fresh trade winds, when low clouds extend upwind of the island, rainfall at the peak of Mount Waialeale is an order of magnitude more than rainfall at Lihue, on the coast 20 km to the southeast. As droplets in a cloud approach the mountain, small vertical wind shear constrains their horizontal motion, while upward motion stops at the trade wind inversion or stable layer. Thus entrainment is limited and droplets grow rapidly. Over the sea and along the coast, drops falling from the cloud usually evaporate. At the mountain face, lifting cools the air. Increased condensation and turbulence accelerate drop growth through collision, as flow becomes constrained between mountain and the trade wind inversion. At the cloud-covered mountaintop, mechanical uplift stops and most of the accumulated moisture precipitates as prolonged light or moderate continuous rain. Although raindrops are rarely more than 2 mm in diameter, daily falls exceeding 50 mm are not uncommon. Besides depending on upwind cloud, Waialeale rainfall is positively related to trade wind strength and depth of the moist layer and negatively to surface dewpoint depression The upper troposphere and the trade wind moist layer are generally decoupled. Changes in the former rarely affect rainfall.
2) During the cool season, significant rain falls on Waialeale from trade wind cloud bands accompanying wind shear lines that extend southwest from midlatitude cold fronts. In summer, the spiral rainbands of dissipating tropical cyclones are responsible for some of the rain. Shorter-lived cloud bands or areas account for the remainder.
3) On average, each year Lihue records thunderstorms on only three trade wind days. On these days, Kauai lay under cyclonically curving winds around a tropical cyclone to the south, or on the northwest side of a small surface trough or cyclone. On almost all other trade wind days, with anticyclonically curving

flow, upper-tropospheric flow favoring upward motion is uncoupled from the lower troposphere, and deep convection cannot develop.

4) Trade wind rain at Waialeale varies diurnally, with a predawn maximum and an afternoon minimum. Nocturnal radiational cooling at the top of the moist layer increases cloud around and upwind of Kauai, and favors droplet growth. The reverse process occurs in the afternoon. This effect is muted when a cloud band is present and disappears during light trade winds when land/sea breeze circulations prevail, favoring an afternoon rainfall maximum.
5) The exceptional trade wind rainfall gradient between windward coast and mountaintop on Kauai is due to a mountain rising to between 1 and 1.5 km (lying within the moist layer) and an island too small to cause upwind slowing (and convergence) in the trade wind or to generate a land breeze when the trade wind is moderate or fresh. Other islands, of similar size and heights, where the moist layer depth is usually around 2 km, should experience similar trade wind rainfall gradients. Besides eastern Oahu, eastern Molokai, and west Maui in the Hawaiian chain, these include Savaii and Upolu in Western Samoa; Tana, Eromanga, and Ambrim in the New Hebrides; Tahiti; Mauritius; and Martinique; over all of them, trade winds are neither as persistent nor as fresh as over Hawaii.

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