Circulations and Rainfall on the Lee Side of the Island of Hawaii during HaRP*

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ABSTRACT

Using aircraft data and portable automated mesonet (PAM) data during the Hawaiian Rainband Project (HaRP; 11 July–24 August 1990), the circulation on the lee side of the island of Hawaii is analyzed. The largest temperature deviations (2–3 K) and negative mixing ratio deviations (−2 to −4 g kg⁻¹) are found in the northwestern and southwestern leeside areas of the island because of the descending trade winds aloft in the lee of low (<2 km) mountain ridges and tops. Rainfall in these areas is much less compared to the central leeside coast (e.g., Kona coast). In these areas, the sea-breeze duration is short compared to the Kona coast because of the presence of opposing trade winds; the wind speed is greater because of larger land–sea thermal contrast. During the stronger trade wind days, adiabatic descent in the lee is more significant and the LCL is higher. As a result, in the northern and southern leeside areas, localized trade wind rain showers driven by local circulations occur mainly under weak trades.

In the Kona area, the mean surface winds are calm behind the massive mountains, with a daytime upslope (onshore) and nighttime downslope (offshore) flow. Along the axis of the return flow in the large wake off the Kona coast, the water vapor content is higher than the ocean upstream, possibly caused by the low-level convergence between the counterrotating eddies along the wake axis. Along the Kona coast, the rainfall in the afternoon hours continues in the early evening and reaches the daily maximum after the onset of the land breezes, possibly because of the lifting of stronger moist return flow by the land-breeze front. Under stronger trade winds, the return flow would be stronger because of stronger island blocking. More rainfall occurs there when trades are stronger.

1. Introduction

The island of Hawaii is the largest island of the Hawaiian island chain, with a diameter of roughly 140 km. Its topography is dominated by two volcanic mountains, Mauna Loa and Mauna Kea, each of which exceeds 4100 m in elevation (Fig. 1). Climatologically, northeasterly trade winds of 5–10 m s⁻¹ are persistent (~70%) throughout the year, especially during the summer months, with the maximum occurrence of 92% of the time in August (Schroeder 1993). Rainfall patterns over the island of Hawaii show a wide degree of spatial variability that is clearly linked to terrain and local winds (Giambelluca et al. 1986).

Previous research on the local circulations and precipitation over the island of Hawaii mostly focused on its windward side because of the presence of the early-morning rainbands offshore (Leopold 1949; Eber 1957; Lavoie 1967; Mendonca 1969; Takahashi 1977; Garrett 1980; Smolarkiewicz et al. 1988; Austin et al. 1996; Chen and Feng 1995, 2001; Wang and Chen 1995, 1998; Carbone et al. 1998; Li and Chen 1999; Frye and Chen 2001; Feng and Chen 2001). Analyses of leeside circulations are few. Leopold (1949) described the trade wind inversion as a “lid” forcing trade wind flow to move around the island. Modeling studies (e.g., Smolarkiewicz et al. 1988) suggest that for a stably stratified flow moving over an isolated mountain barrier, the Froude number (Fr = U/Nh, where U is the upstream wind speed, N is the Brunt–Väisälä frequency, and h is the height of the barrier) characterizes the behavior of the flow. For typical trade wind conditions over the Hawaiian Islands, the Froude number is between 0.2 and 0.5 and the low-level flow is predicted to be deflected around the island. In the Kona area, the daytime upslope flow driven by solar heating produces convective rainfall on the slopes (the “coffee belt”) in the afternoon hours (Leopold 1949; Schroeder et al. 1977). This process is most important during the summer months and results in the only summer rainfall maximum (Giambelluca et al. 1986) within the state. Using the data collected at six stations over northwestern Hawaii, Schroeder (1981) suggested that sea-breeze variability appears to be related to both synoptic-scale cloud
and trade winds and the thermal properties of the lava surface.

The airflow over the ocean on the lee side of the island of Hawaii was first reported from ship observations over a 15-yr period (Patzert 1969). The composite airflow shows the existence of a quasi-stationary cyclonic vortex to the north and an anticyclonic vortex to the south (Fig. 3 of Patzert 1969). The maximum rainfall along the Kona coast (Taliaferro 1958) coincides with the convergent airflow between the cyclonic and anticyclonic eddies to the west of the island. Patzert (1969) also noted that the annual rainfall maximum in the Kona area occurs during the summer months when the trade winds are most persistent. He speculated that the Kona rainfall might be related to the offshore convergence.

The first aircraft probing of the wake of the island of Hawaii was made in the summer of 1980 (Nickerson and Dias 1981). The data from an aircraft flight contained the first direct evidence for the existence of atmospheric vortices in the wake. During the Hawaiian Rainband Project (HaRP; 11 July–24 August 1990), five Electra flights were designed to study the mesoscale fields downstream of the island of Hawaii. Detailed horizontal structure of the Hawaiian wake in low levels was presented by Smith and Grubišić (1993, hereafter referred to as SG93). They showed that the wake consists of two elongated counterrotating quasi-steady eddies (hereafter referred to as the large wake) that give rise to a wide region of strong reverse flow along the wake axis (or the return flow) with a stagnation point offshore. A small Kohala wake (hereafter referred to as the small wake) is embedded between the accelerating trade winds to the north and the Waimea jet (strong winds channeling through the Waimea Saddle) to the south, with a weak return flow in the lee of the Kohala Mountains (Fig. 18 of SG93). At the eastern edge of the wake, the eddies are potentially warmer and more humid than the surrounding trade wind air. Air in the shear zones between the accelerated trade winds to the north and south of the island and the recirculating wake is warm and dry.

To date, there has been no comprehensive analysis of the circulations on the lee side of the island of Hawaii because of the lack of a dense observational network. Chen and Nash (1994) used high-resolution portable automated mesonet (PAM) data from HaRP to document
the climatology of the surface airflow and rainfall occurrences during the diurnal cycle over the entire island. They found that most areas are dominated by daytime upslope and nighttime downslope wind components separated by morning and evening transitions. Chen and Wang (1994) suggest that, in addition to the diurnal heating cycle, the thermodynamic fields over the island are also related to orography, airflow, and distributions of clouds and rainfall. They found that on the windward side west of Hilo where the mean winds are weak because of the island blocking, the onset of daytime upslope and nighttime downslope flow is determined by the thermal contrast between the surface air and the open-ocean environment at the same level. These results are consistent with the analysis of Carbone et al. (1995).

The 50 PAM stations deployed during HaRP provide a unique opportunity to study the circulations on the lee side of the island of Hawaii and the role of dynamic blocking and thermally driven local circulations on the production of summer rainfall. On the Kona lee side, the mean surface winds are calm (Chen and Nash 1994) because trade winds are blocked by the massive mountains extending well above the trade wind inversion. In contrast to the Kona area, the northernwestern and southwestern leeside coasts are well exposed to trade winds, since the heights of mountain tops and ridges to the east are lower than the typical height of trade wind inversion (~2 km). In this study, diurnal circulations and rainfall regimes on the lee side under different trade wind exposures (e.g., Kona versus northernwestern and southwestern leeside coasts) will be studied. The flight-level data collected by aircraft missions on the lee side will be compared with the PAM data over land to study land−sea thermal contrast during the diurnal heating cycle. To study the effects of island blocking (Smolarkiewicz et al. 1988) and descending airflow in the lee (Chen and Wang 1994) on the leeside airflow and rainfall, a comparison is made between the strong and the weak trade wind cases. Data used are given in section 2. The thermal fields in the wake zone are presented in section 3. Section 4 shows the diurnal variations of leeside thermal fields and winds during HaRP. The effects of trade wind strength on the leeside thermal fields and wind patterns are discussed in section 5. Analyses of rainfall regimes on the lee side are presented in section 6. Finally, the summary and conclusions are given in the last section.

2. Data

Two aircraft missions (6 and 24 August) taken by the National Center for Atmospheric Research (NCAR) Electra aircraft during HaRP are used in this study. Horizontal distributions of thermal fields in the wake zone were analyzed by using the flight-level data collected 460−510 m above sea level. Since the data collected by the NCAR Electra were not taken at the same height, we used the flight-level thermodynamic data taken by the aircraft during ascent over the open ocean upstream of the island on the same day as the reference. The deviations from the open-ocean values upstream of the island at the same level were computed. On 24 July, the data used for the wake analysis were collected between 0640 and 1000 Hawaii standard time (HST). In the small wake on the lee side of the Kohala Mountains, the data between 0752 and 0919 HST on 6 August were used for the analysis of horizontal distributions of the thermal fields. Detailed information on flight patterns and data are given in SG93.

During HaRP, a total of 22 days with an aircraft sounding during ascent ~90 km east of the island of Hawaii were available. The lowest flight altitude was approximately 150 m. We extrapolated each aircraft sounding from flight-level data during ascent to the sea level from the lowest flight altitude by assuming that the lowest levels were well mixed with constant potential temperature and mixing ratio (Chen and Wang 1994). These soundings were composited to obtain the mean sounding over the open ocean (Fig. 2 of Chen and Wang 1994). We assume that the mean early-morning sounding represents the mean upstream thermodynamic structure of the incoming trade wind flow during HaRP.

During HaRP, 12 days (11, 13, 24, 25, 28 July and 8, 9, 12, 13, 16, 18, 23 August) were classified as strong trade wind days by Chen and Nash (1994). They also classified 12 weak trade wind days (15, 20, 21, 27, 29, 30 July and 3, 5, 7, 19, 20, 21 August). The 12 strongest (weakest) trade wind days were determined from the averaged daily (0000−2400 UTC) resultant winds at the northernmost (station 31) and southernmost stations (station 1) for days on which northeasterly trade winds were present (from the inspection of surface maps). Among the 22 days when an upstream sounding was taken by the aircraft, the mean wind speed and direction between 500 and 1500 m for these soundings are 4−11 m s$^{-1}$ and 50°−110° from the north, respectively. Only 24, 28 July and 8, 9, 16 August are among the strong trade wind days, 20, 30 July and 3, 20, 21 August are among the weak trade wind days. The five upstream soundings during these weak (strong) trade wind days are composited to represent the averaged thermodynamic structure of the weak (strong) trade wind flow (Fig. 2). The composite strong trade wind sounding is slightly drier than the composite weak trade wind sounding. Below 2.5 km, the mean temperature is almost the same for both cases. Above 2.5 km, the temperature for the strong trade wind days is slightly higher than for the weak trade wind days. The standard deviations of temperature and dewpoint are about 1 K for both cases. The mean wind direction between 500 and 1500 m varies from 76° to 91° and 71° to 107° for the 5 strong and weak trade wind days, respectively. The averaged wind speeds and directions are 8.2 m s$^{-1}$ and 83° for the strong trades and 6.5 m s$^{-1}$ and 90° for the weak trades. The standard deviations of wind speed are 1.1 and 0.7 m s$^{-1}$, respectively. These winds are taken instantaneously by the aircraft during ascent. Even the wind direction
vars from one sounding to another. There are no dramatic systemic differences in the wind direction between these two groups of soundings. Rasmussen et al. (1989) show that for Fr = 0.2, as the wind direction changes from east to northeast, the flow sees a progressively narrow obstacle in their numerical experiments. Under the northeasterly trade wind flow, their model simulated a cyclonic eddy off the southwestern coast of the island. Daily satellite pictures show considerable day-to-day variations of the lee eddies that may be related to the differences in trade wind conditions over the open ocean. The effects of trade wind direction on the leeside circulation and rainfall will be investigated in the future.

The PAM data were sampled at 1-min intervals. We use the 15-min-averaged data processed by Chen and Nash (1994) from the 1-min data. The deviations of the thermal fields at the leeside PAM stations from the upstream conditions at the same level were computed using the upstream soundings taken by the NCAR Electra aircraft as the references. For the HaRP mean, the mean of 22 upstream soundings is used as the reference. For the strong (weak) trade wind composite, the average of the five strong (weak) trade wind aircraft soundings is used as the reference. Since the upstream sounding is not available on a daily basis, it is not possible to compute the variance for the deviations from the upstream value. We compute the standard deviations for temperature and water vapor mixing ratio for both the weak and strong cases throughout the diurnal cycle. For both cases, the standard deviations for leeside stations are about 0.5–1.5 K for surface air temperature and 0.5–1.0 g kg⁻¹ for water vapor mixing ratio. The variance of surface air temperature is higher on the slopes whereas the variance of mixing ratio is larger along the coast.

3. The thermal fields of the wakes

Figure 3 shows the thermal field deviations from the upstream aircraft sounding in the open ocean for the large wake at ~490 m above sea level, constructed from the data collected from 0640 to 1000 HST on 24 July. The temperature deviations for the entire large wake are positive (Fig. 3b) because of the generally descending airflow in the lee. Note that during the summer months, the northeasterly trade wind flow extends well above the trade wind inversion (Feng and Chen 2001) (Fig. 2).

In the leeside areas off the northwestern and southwestern coasts, the mixing ratio is the lowest, with a negative maximum deviation of about -3.5 g kg⁻¹. The positive temperature deviation is the largest there (~3 K). Part of the warming and drying in the lee could be related to condensation on the windward side. However, this process is not the primary reason for the observed warming and drying in the leeside areas. For moist adiabatic processes, the moist static energy (h = CₚT + gZ + Lq) is conserved, where Cₚ is the specific heat at constant pressure, T is the temperature, g is the gravitational acceleration, Z is the geopotential height, L is the latent heat of condensation, and q is the specific humidity. The depletion of 1 g kg⁻¹ of water vapor due to condensation would result in warming of about 2.5 K. Assuming that warming in the lee was solely caused by condensation heating on the windward slopes, it would have accounted for only about one-third of the observed depletion of water vapor in these areas. The moist static energy deviation is negative off the northwestern and southwestern coasts (Fig. 3c). Furthermore, the aircraft observations off the leeside coast were made in the early morning with relatively clear skies over the windward slopes (Chen and Nash 1994). It is apparent that the descending flow in the lee (Fig. 4) is the main mechanism that accounts for the drier and warmer conditions in the lee with a lower moist static energy. The mountain ridges and tops of the southern and northern parts of the island are lower than the trade wind inversion height (~2 km). Thus, the trade winds aloft beneath the inversion could move over these low mountain ridges and tops and descend to lower levels in the lee (SG93; Chen and Wang 1994), producing the warmest and driest conditions in these areas. It appears that the drier and warmer conditions on the leeside slopes found by Chen and Wang (1994) extend farther downstream offshore. SG93 found hydraulic jumps in the accelerated trades to the north and south of the island with an abrupt decrease.
in speed. The jumps are also discernible as abrupt changes in potential temperature and moisture. Without aircraft data over land, it is not certain if the jumplike discontinuities exist above the leeside slopes or not. This possibility will be investigated in the future from results of high-resolution mesoscale models.

Along the axis of the return flow of the large wake offshore, the positive temperature deviations are smaller than the northwestern and southwestern leeside coastal areas; the mixing ratio deviations are positive. The rest of the wake has negative mixing ratio deviations (Fig. 3a). Unlike other areas in the lee, the moist static energy deviations are positive along the wake axis (Fig. 3c). It appears that the high moist static energy air in the lowest levels is transported upward by the low-level moisture convergence along the wake axis between the counter-rotating eddies. From satellite pictures, a long cloud band is frequently observed along the wake axis, extending several hundred kilometers downstream (SG93).

Thermodynamic fields for the small wake on the northwestern lee side of the island of Hawaii were also constructed from the data collected between 0750 and 0919 HST on 6 August (Fig. 5). Similar to the 24 July case, the air temperature in this area is higher than the upstream air at the same level (Fig. 5b). The largest air temperature deviations of nearly 3 K are found near the coastline. Corresponding to the large positive temperature deviations there, the mixing ratios are lower (Fig. 5a), with negative moist static energy deviations (Fig. 5c).

4. Diurnal variations of leeside circulations

In this section, the diurnal cycles of the averaged surface winds and thermal fields along the Kona transect (stations 40, 41, and 42 in Fig. 1), the Waimea Saddle transect (stations 36, 37, 28, 26, and 27), and the leeside coastal transect (stations 31, 32, 33, 36, 39, 40, 45, 46, and 1) will be presented.

a. Kona transect

The averaged diurnal cycles of the surface winds and the surface temperature deviations along the Kona transect are shown in Fig. 6. In the lee of massive Mauna Loa (elevation > 4100 m), with mean calm surface

Fig. 3. Deviations of the thermodynamic fields from the upstream open-ocean conditions at the same level in the large wake at about 490 m above sea level from 0640 to 1000 HST 24 Jul: (a) mixing ratio \( \text{g kg}^{-1} \), (b) temperature (K), and (c) moist static energy \( \text{10}^1 \text{J kg}^{-1} \).
winds (Fig. 4a), the thermally driven diurnal winds dominate (Leopold 1949), with sea-breeze/upslope flow during the daytime and land-breeze/downslope flow at night. The transition from the land-breeze/downslope to sea-breeze/upslope flow in the early morning occurs around 0800 HST. At that time, the thermal contrast between the surface air temperatures over land and the upstream trade wind flow on the windward side rises above 2 K. The shift from the sea-breeze/upslope to land-breeze/downslope flow during the evening transition is a slower process than the morning transition because of slow land surface cooling as compared to the rapid land surface heating after sunrise. The evening transition occurs after the deviations of the surface air temperatures drop below 1 K. As shown in the last section, the temperature in the return flow off the Kona coast is about 1.5 K higher than the incoming trade wind flow offshore off Hilo. Therefore, the turning of surface winds in the early morning occurs immediately after the surface air over land becomes warmer than its downstream environment off the Kona coast. In the evening, the turning of winds occurs immediately after the surface air over land becomes negatively buoyant. These results are similar to those of the Hilo Bay area (Chen and Feng 1995), where the mean surface winds are also weak (Chen and Nash 1994) because of island blocking.

In the early morning, the surface air temperature at station 42 (elevation 1555 m) on the upper slopes rises more rapidly than at the other two stations along the Kona transect because of significant surface heating over the relatively dry soil on the leeside upper slopes. The maximum temperature deviation at station 42 is greater than 4 K around noon. With relatively higher temperature deviations, the upslope wind speed at station 42 during the day is also slightly stronger (3 m s⁻¹) than at the other two stations (1–1.5 m s⁻¹). In the afternoon hours, with an extensive orographic cloud cover over the lower Kona slopes (Chen and Feng 1995), the temperature deviations at station 41 (elevation 729 m) are the smallest among these three stations. The surface air temperature at station 41 also drops below the environment value (~1.5 K) first, with the earliest turning of winds from upslope to downslope flow.

b. Waimea Saddle transect

The composite surface winds along the Waimea Saddle transect (stations 36, 37, 28, 26, and 27) show that strong easterly trade wind flow prevails over the Waimea Saddle (stations 28, 26) throughout the day (Fig. 7a) as the trades are channeled through the saddle. The hydraulic jump may occur here, but, with only surface data, we are unable to verify its existence. In the semi-arid region immediately downstream of the saddle (station 28), the surface winds exhibit notable diurnal variations, possibly caused by the downward transport of trade wind momentum as a result of vertical mixing in the afternoon hours (Schroeder 1981). The wind speed maximum (9 m s⁻¹) in the afternoon hours is slightly larger than the mean upstream trade wind speed over the open ocean (8 m s⁻¹). Because of the strong easterly winds through the saddle (the Waimea jet), the sea breezes on the lee side only occur along the Waikoloa coast (station 36) for the HaRP mean. Their duration is short (1000–1700 HST) as compared to the Kona area. For the inland station 37 (elevation 358 m), the sea-breeze front could reach there in the afternoon hours only under weak trade wind conditions (see next section). In the afternoon hours, the maximum positive temperature deviations are observed at station 37 (>6 K). As shown in section 3, temperature deviations between the air of the small wake off the coast and the upstream air at the same level are about 3 K. Thus, in
the early afternoon, the thermal contrast between station 37 and the downstream environment is about 3 K. Nevertheless, under strong opposing easterly flow (9 m s\(^{-1}\)), the mean winds at station 37 do not exhibit an upslope wind component in the early afternoon despite the presence of positive thermal contrast (Fig. 7a).

The warm and dry conditions (Figs. 7a,b) caused by the descending airflow on the lee side of the Waimea Saddle persist throughout the diurnal cycle. The warmest and driest conditions are observed on the leeside slope in the vicinity of station 37 (elevation 358 m), especially in the afternoon hours with a decrease in stability. Because of the low heat capacity, relatively small albedo, and very little soil moisture of the lava sand, the surface air temperature increases rapidly after sunrise under clear skies. At station 36 along the coast, sea breezes in the afternoon hours bring in relatively moist and cool air from the ocean.

c. Leeside coastline transect

Along the leeside coastline, the surface air temperatures are persistently higher at stations 33, 36, and 46 than at other stations (Fig. 8a) along the transect. Station 33 is located on the lee side of the Kohala Mountains. Station 36 is downstream of the Waimea Saddle, whereas station 46 is located on the southwestern corner of the island. The warmer, drier conditions in these coastal areas (Fig. 8) and the adjacent oceans (Fig. 3) are apparently caused by descending airflow aloft in the lee.
The strength and duration of the sea breezes in the leeside areas of the island of Hawaii are determined by two factors: trade wind exposure and temperature contrast. Because of the strong winds moving around the corners of the island, stations at the northern (stations 31, 32) and southern (stations 46, 1) ends of the leeside coast do not exhibit an onshore wind component in the afternoon hours (Fig. 8a). These stations show a stronger easterly trade wind component in the afternoon hours. The afternoon sea breezes are stronger along the Waikoloa coast (stations 33, 36, and 39) than along the Kona coast (stations 40 and 45) because the temperature deviations during the day are higher at the former stations. The strongest onshore flow occurs along the Waikoloa coast (station 36), which is the region that has the largest land–sea thermal contrast during the day. Even though the daytime temperature deviations on the lee side of the Kohala Mountains (station 33) are larger than at station 36, the largest positive temperature anomalies on the lee side of the Waimea Saddle occur inland (in the vicinity of station 37) (Fig. 7). The daytime temperature anomalies there are larger than at station 33. The weakest onshore flow occurs along the Kona coast where the daytime land–sea thermal contrast is the smallest. Along the Kona coast, with the absence of opposing trade winds at the surface, the sea breezes...
there last longer than at any of the stations along the leeside coastline transect.

5. Effects of trade wind strength

The horizontal distribution of the averaged surface wind differences between the 12 strongest and the 12 weakest trade winds during HaRP is shown in Fig. 4b. Chen and Nash (1994) show that along the Waikoloa coast sea breezes are of shorter duration (≈6 h) under strong opposing trade winds as compared to the weak trade wind cases (≈10 h). In this section, the effects of the trade wind strength on the thermodynamic fields and circulations on the lee side of the island of Hawaii will be presented.

a. Mean fields

Chen and Wang (1994) have identified three areas with relatively warm and dry conditions over the island of Hawaii caused by a descending airflow from aloft in the lee: the Waikoloa coast, the southwestern corner, and the southeastern coast on the lee side of the Kilauea volcanoes. These regions have slightly larger positive temperature deviations and negative moisture deviations (Fig. 9) when the trade winds are stronger because of a stronger descending airflow aloft. In contrast, in the Kona area where trade winds are absent at the surface, there are no significant differences in the surface air temperature deviations and winds between the strong and weak trade wind cases. The negative mixing ratio deviations along the Kona coast are smaller when trade winds are stronger, with higher positive deviations on the lower Kona slopes (Fig. 9), possibly due to a stronger return flow in the wake. The counterrotating eddies in the wake should be stronger, with a larger low-level convergence along the axis of the return flow (SG93) when trade winds are stronger. More moisture would be transported upward from the sea surface when the low-level convergence is more significant.

![Fig. 9. Thermal-field deviations from the upstream open-ocean values at the same height above the sea level for the 12 strong trade wind days and the 12 weak trade wind days: (a) temperature and (b) mixing ratio.](image-url)
b. Diurnal cycle

1) Kona transect

In the Kona area, the winds are dominated by the daytime upslope/onshore, nighttime downslope/offshore flow for both the strong trade wind and the weak trade wind cases (Fig. 10). The diurnal variations in the surface air temperatures are similar in both cases. Similar to the HaRP mean, the onset of onshore flow occurs at about 0800 HST in the morning; wind shift in the early evening occurs at about 1900 HST for both cases. On the other hand, the mixing ratio deviations along the coast are positive between 0900 and 2000 HST, with larger positive deviations on the lower Kona slopes during the day and in the evening when the trade winds upstream are stronger (Fig. 10).

2) Waimea Saddle transect

With the presence of opposing trade wind flow through the Waimea Saddle, the combined sea-breeze/upslope flow could reach station 37 in the afternoon hours only during weak trade winds (Fig. 11). Even though the duration of sea breezes along the Waikoloa coast (station 36) is shorter under stronger opposing trade wind flow, their strength is slightly greater. With
a stronger trade wind flow moving through the saddle, the adiabatic descent in the lee is more significant with warmer temperatures (Fig. 11), especially during the daytime. The stronger sea breezes along the coast under stronger opposing trade winds are apparently caused by larger land–sea thermal contrast.

3) Leeside Coastline Transect

Similar to the HaRP mean, for both the strong and weak trade wind days, trade winds move around the northern (stations 31, 32) and southern (stations 46, 1) ends of the island without an onshore wind component during the daytime (Fig. 12). Other stations along the leeside coastline transect (e.g., stations south of station 32 and north of station 46) exhibit an onshore wind component during the daytime hours. For these stations, except in the Kona area (station 40), the land–sea thermal contrast during the day is larger as the stronger trade wind flow aloft moves over the mountain ridges and descends in the lee. The daytime onshore flow is stronger under stronger trades.

There are differences in the duration of the daytime onshore flow between the strong and weak trade wind days (Fig. 12). Among these stations, station 36 downstream of the Waimea Saddle has the largest difference
in the duration of daytime onshore flow (6 versus 10 h) between the two cases. For the strong trade wind days, the ending time of the onshore flow at station 36 is about 3 h earlier than for the weak trade wind days. Perhaps the downward transport of trade wind momentum (Schroeder 1981) would result in the early ending of the onshore flow in the late afternoon hours when trade winds are stronger. Note that station 36 is downstream of the Waimea jet.

6. Rainfall on the lee side

Chen and Nash (1994) show that, except in the Kona area, leeside areas are dry with much less precipitation than most of the windward regions. In this section, the rainfall characteristics on the lee side will be studied. The role of island blocking (Patzer 1969) and diurnally driven circulations (Leopold 1949; Schroeder et al. 1977) on the production of summer rainfall will be investigated.

a. Kona area

On the leeside slopes (stations 41, 42), rainfall mainly occurs in the late-afternoon hours (1500–1800 HST) before the turning of surface winds during the evening transition and diminishes after the onset of downslope winds (Fig. 13). Even though the orographic lifting by the upwarp flow is the main reason for the development of rainfall on the leeside slopes (Leopold 1949; Schroeder et al. 1977), the diurnal rainfall maximum does not occur in the early afternoon (Fig. 13), when the upwarp flow is the strongest (Fig. 6). The maximum rainfall and rainfall frequency on the leeside slopes occur in the late afternoon before the turning of surface winds from the upwarp to the downslope flow. Note that the lifting condensation level (LCL) has substantial diurnal variation (Fig. 14a). It reaches the highest level (∼600 m) before noon because of surface heating and decreases rapidly in the afternoon hours. The onshore/upwarp flow brings in moist air. The surface air temperature decreases in the afternoon hours. Therefore, the LCL becomes lower in the late afternoon than earlier in the
OCTOBER 2003  YANG AND CHEN

FIG. 14. (a) Diurnal cycle of mean LCL (m) above the ground during HaRP for stations 40 (solid line), 41 (dotted line), and 42 (dashed line). (b) Diurnal cycle of mean LCL (m) above the ground for the 12 strong trade wind days (solid line) and the 12 weak trade wind days (dotted line) at station 40. (c) Diurnal cycle of mean LCL (m) above the ground for the 12 strong trade wind days (solid line) and the 12 weak trade wind days (dotted line) at station 33.

1. Northwestern lee side

Rainfall in the northwestern leeside areas is infrequent (Fig. 15c) because of the descending airflow aloft. For the 12 strongest trade wind days, the trade wind rain showers are suppressed on the lee side of the Kohala Mountains, downstream of the Waimea Saddle and over the southwestern corner of the island (Fig. 16a). In fact, less than 1 mm total rainfall was recorded at stations 33, 36, 37, 32, and 39 for the 12 strongest trade wind days during HaRP.

At station 37 on the lee side of the Waimea Saddle, rainfall mainly occurs in the afternoon hours (Fig. 16) as the combined sea-breeze/upslope flow converges with the trade wind flow moving through the saddle (Schroeder 1981). Nevertheless, the hourly rainfall frequency in the afternoon hours there is only about 10% (Fig. 16). An examination of the daily rainfall shows that afternoon rain showers at station 37 occurred only on 15 (7 mm), 16 (33 mm), 17 (1 mm), 20 (11 mm), 21 (7 mm), 29 (4 mm) July, and 23 (1 mm) August during HaRP. On these days, except 23 August, a low pressure system moved through the mid-Pacific, north of the island chain, with weak trades. As a result, trade winds were weaker than normal. Note that 15, 20, 21, and 29 July are among the 12 weakest trade wind days during HaRP. Under stronger trade winds, sea breezes are stronger along the Waikoloa coast in northwestern Hawaii (Fig. 11). Both the orographic lifting of the combined sea-breeze/upslope flow and the localized convergence between the sea-breeze/upslope flow and trade winds would be more significant if trade winds were stronger. Nevertheless, under normal or strong trade wind conditions, it is unlikely for local trade wind rain showers to occur in this region because of the significant descending flow aloft.

2. Leeside coastline transect

On the lee side of the Kohala Mountains (station 33), no rainfall is recorded throughout the diurnal cycle for the 12 strongest trade wind days. Rainfall was recorded only on 15 (27 mm), 19 (3 mm), 20 (48 mm), 21 (15 mm), 31 (6 mm) July, and 24 (2 mm) August. In other words, as at station 37, most of the rainfall during HaRP occurred during two periods (15 July and 19–21 July), when a midlatitude low pressure system passed through the mid-Pacific to the north of the Hawaiian island chain with weak trades. During the daytime, warm and dry
conditions are persistent in the lee with a high LCL (Fig. 14c). No rainfall was recorded between 0400 and 1400 HST. With the presence of localized convergence between the onshore flow and the descending trade wind flow in the lee and a lower LCL, rain showers are possible in the late afternoon under weak trades (Fig. 17). The rainfall was also recorded in the evening hours after the onset of the offshore flow for the weak trade wind cases, possibly because of the lifting of the return flow in the small wake off the coast by the land-breeze front.

The southwestern corner (station 46) is another area with very little rainfall (~1 mm) during the 12 strongest trade wind days. Only ~3 mm of rainfall occurs during the 12 weakest trade wind days (Fig. 15). Rainfall over south Kona (station 45) occurs primarily under weaker trades (Fig. 15) in the afternoon hours (Fig. 17) and diminishes after the onset of downslope flow (2000 HST; Fig. 12b). Both the orographic lifting by the upslope flow and the convergence between the incoming trade wind flow (Fig. 4a) and the upslope flow in the afternoon hours may be important for the observed rainfall maximum in the afternoon hours under weak trade wind conditions. Along the Kona coast, the moisture content and rainfall along the wake axis are higher under stronger trade winds. A schematic diagram summarizing the effects of trade wind strength on rainfall on the lee side is given in Fig. 18.

At the northern and southern ends of the leeside coasts (stations 31 and 1), without a daytime onshore flow, both the rainfall frequency and the hourly rainfall accumulation have a nocturnal maximum. At station 1, more nocturnal rainfall (42 mm) occurs during the 12 weakest trade wind days as compared to the 12 strongest trade wind days (7 mm). Drier and warmer conditions are more pronounced during the daytime, especially during the strong trade wind days. Furthermore, the horizontal wind shear between the offshore flow from the southeastern coastline at night and trade winds moving around the corner is more significant under weaker trade winds (Fig. 16a of Chen and Nash 1994). Another reason for the nocturnal rainfall maximum in the lee of the northern and southern ends of the island may also be related to the conditions of the open ocean, where trade wind cloudiness may exhibit a nocturnal maximum due
7. Summary and conclusions

The island of Hawaii has long been considered a natural laboratory for studying precipitation formation and interactions between microphysical processes and flow dynamics. In the past, several field projects have been conducted over the island. The most recent one is HaRP. However, most studies have focused on the precipitation and circulation on the windward side. Work and research on the leeside circulations are few. In this paper, we use the aircraft and PAM data collected during HaRP to analyze the local circulations and rainfall on the lee side of the island.

At the aircraft flight level (~490 m), the temperatures in the wake zones (the large wake and small wake) are higher than at the upstream environment at the same level because of the general descending airflow on the lee side. The highest temperature deviations (2–3 K)
FIG. 17. As in Fig. 13, but for stations (a) 31, (b) 33, (c) 1, (d) 46, and (e) 45.
and the lowest mixing ratio deviations (2–4 g kg$^{-1}$) are observed off the northwest and southwest coasts of the island as a result of significant adiabatic descent of trade winds aloft to low levels. The return flow off the Kona coast in the large wake (SG93) has a higher moisture content than the open-ocean upstream. The higher moisture content there is caused by the low-level convergence between the counterrotating eddies (SG93) along the wake axis.

In the Kona area, where the mean surface winds are calm behind the massive Mauna Loa (elevation > 4100 m), the diurnal variations of local winds are mainly driven by the land–sea thermal contrast. On the Kona slope, the diurnal rainfall maximum occurs in the late afternoon because of orographic lifting (Leopold 1949; Schroeder et al. 1977), when the LCL is lower (~200 m) than earlier in the day. Along the coast, the precipitation in the late afternoon continues after the onset of the offshore flow. The diurnal rainfall maximum along the coast occurs in the early evening, possibly caused by the lifting of the moist return flow offshore by the land-breeze front. For the composite of the 12 strong trade wind days, the rainfall along the coast is higher than the 12 weak trade wind days, possibly because of a stronger return flow offshore that is due to stronger island blocking.

Along the northwestern coast downstream of the Wai- mea Saddle, because of strong opposing trade winds channeling through the saddle, the duration of sea breezes is short as compared to other leeside coastal stations. Along the leeside coastline, the longest duration of sea breeze is found in the Kona area. The strongest (weakest) onshore flow occurs at station 36 (40) along the Waikoloa (Kona) coast, which is the region that has the largest (smallest) daytime land–sea thermal contrast. For leeside stations where daytime sea breezes develop under the opposing descending trade winds, the duration of sea breeze is shorter and ends earlier (<3 h) when trade winds are stronger. The downward transport of trade wind momentum in the afternoon hours (Schroeder 1981) may be more significant when trade winds are stronger and may account for the earlier ending of the onshore flow.

In the northwestern and southwestern leeside areas, rainfall is much less, as compared to the Kona coast, as a result of descending airflow aloft, especially during strong trade wind days. In these areas, localized trade wind rain showers driven by local circulations occur mainly under weak trades. Along the leeside coast of the Kohala Mountains, the diurnal rainfall has a maximum in the late evening, possibly because of the convergence between the offshore flow and the return flow.
in the small wake. In south Kona, the diurnal rainfall maximum occurs in the afternoon hours because of the development of upslope flow. At the southern and northern tips, the onshore flow fails to develop during the day as strong trade winds move around the corners. The rainfall there has a nocturnal maximum, especially under weak trade wind cases.

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