

# Diurnal Weather Patterns on Oahu and Lanai, Hawaii

LUNA B. LEOPOLD<sup>1</sup>

## INTRODUCTION

WEATHER FORECASTING in the Pacific area has been predominantly aimed at serving airplane operations. On the other hand, little or no developmental work has been done to provide bases for weather forecasts for agriculture. In Hawaii the two largest industries are agricultural—the growing of sugar cane and pineapples. Techniques and organization to provide both long- and short-range forecasts would be of considerable aid to these industries.

Though a long-continued interest in weather on the part of agriculturists in Hawaii is shown by a large number of rain gages and temperature measurements, detailed analyses involving additional critical data are required to give accurate pictures of the variations of meteorological elements over the diverse topographic areas of the islands. A better over-all description of these factors is an early step in the development of a sound basis for local forecasting.

Hawaii, lying in the trade-wind zone, experiences relatively small, day-to-day variations in weather when compared with a continental locality in the belt of westerlies. Yet great differences in ecologic habitats are found within very short distances. Day-to-day synoptic changes are subtle and difficult to follow, owing to the wide expanses of ocean where no upper air data are obtainable. Particularly in such circumstances, the study of diurnal fluctuations may contribute to a better understanding of the manner in which the great local differences originate.

Figures 1 and 2 show the location of stations on Oahu and Lanai which are discussed in this paper. The profiles drawn in the direction of

the prevailing trade wind, ENE-WSW, provide some picture of the topography. On Oahu, the two ranges of mountains are oriented nearly perpendicular to the trades, and, therefore, provide barriers causing large differences in orographic rainfall. These have been discussed in connection with the mean annual isohyets of Voorhees (1929) and by Nakamura (1933), Wentworth (1946), and others.

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## DIURNAL RAINFALL PATTERNS

As described previously, rainfall in Hawaii results primarily from orographic effects on the trade winds, from frontal passages, and from easterly waves. Most "kona" storms are actually related to frontal passages.

Kona weather is a local term which often is erroneously used to imply a condition of south wind. A better translation for the word kona is "leeward," and in terms of weather, it implies a cessation of the normal northeasterly trade wind. This ordinarily causes a strengthening of onshore sea breezes.

On the southern coast of Oahu, for example, northeasterly winds blow more or less continually during ordinary trade-wind weather in spite of a tendency for an onshore sea breeze to develop in the afternoon. When the trade wind decreases, the sea breeze asserts itself.

On even more sheltered leeward coasts an afternoon sea breeze is the rule, and a decrease

<sup>1</sup> Meteorologist, Pineapple Research Institute of Hawaii. Manuscript received September 11, 1947.

in trade wind is accompanied by an increase in the onshore flow.

The trade-wind decrease is commonly associated with the passage of a front or pressure trough. In such instances, the wind direction over the ocean tends to change to south or southwest preceding the pressure trough, and veering to westerly in the area behind the trough. The tendency for reversal in wind direction from the northeasterly trades accounts

for an inflow of warmer air from lower latitudes.

It can be seen, therefore, that "kona" weather cannot be interpreted as "south-wind weather" except in particular localities, and it follows that "leeward" is a more correct interpretation of the term.

Frontal storms are those related to pressure troughs in the westerly winds aloft. This westerly circulation is strongest in winter. In summer the trade winds reach higher levels as the

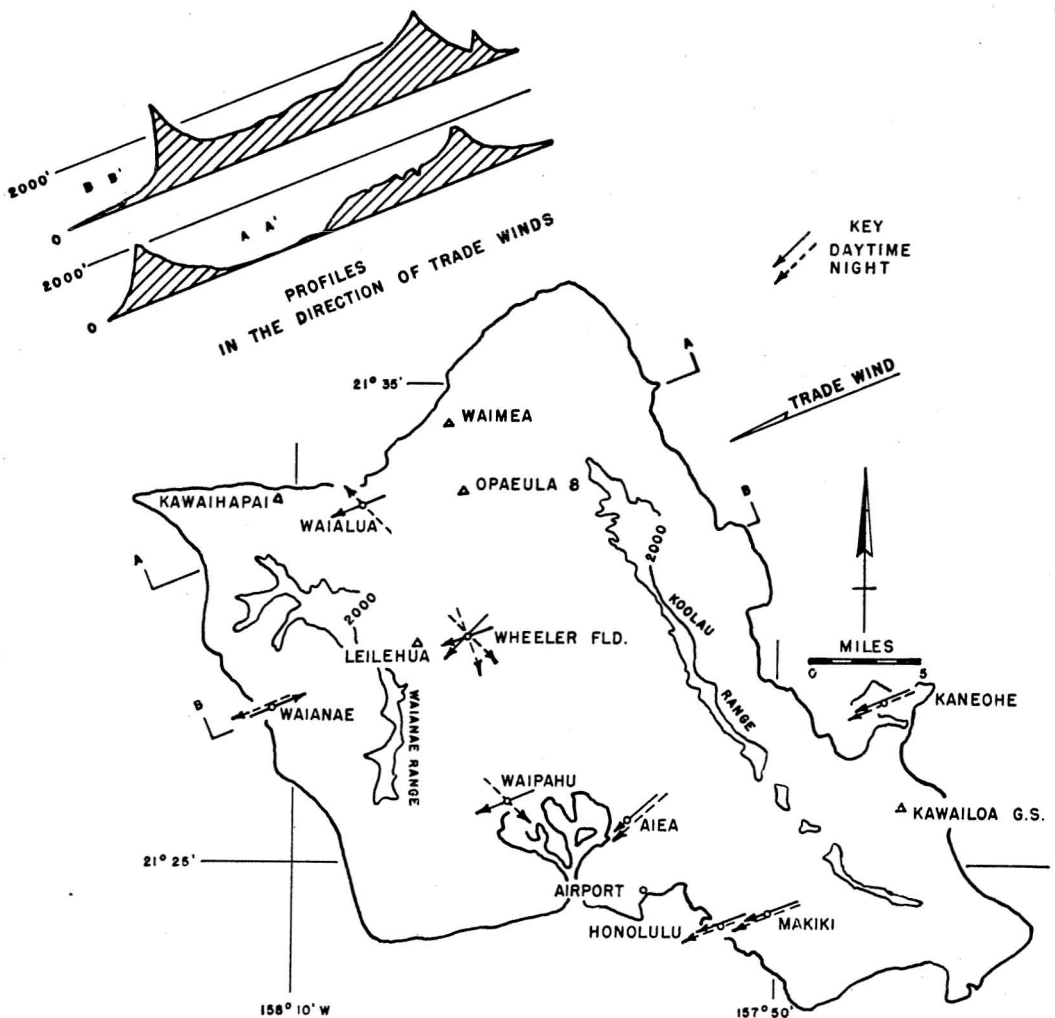


FIG. 1. Map of Oahu showing location of stations and day and night wind directions.

strength of the easterly circulation around the Pacific high-pressure cell increases. Pressure troughs in this system of easterly winds also move in the direction of the wind, in this case from the east. These disturbances, called "easterly waves," provide, in summer, decks of high clouds as well as an increase in height and size of the normal fair-weather low clouds of the ocean.

The importance of convective rain in the Territory has not been sufficiently emphasized. Rain or showers from cumulus or cauliflower clouds are often seen over the open ocean or over the lower and drier portions of the Hawaiian Islands, particularly in the afternoon.

Though well-developed thunderstorms are rare in the area, convective clouds built up sufficiently to yield rain are experienced during periods when the temperature inversion aloft becomes weak or disappears. The stability of the layer through the temperature inversion and the dryness of the air above the inversion ordinarily limit the height of development of cumulus clouds.

Convective storms are sufficiently important to bear a local name, "naulu," used on the islands of Maui, Lanai, and Molokai. It refers to a type of rain which occurs primarily in the afternoon, and which is characterized by short duration and high intensity.

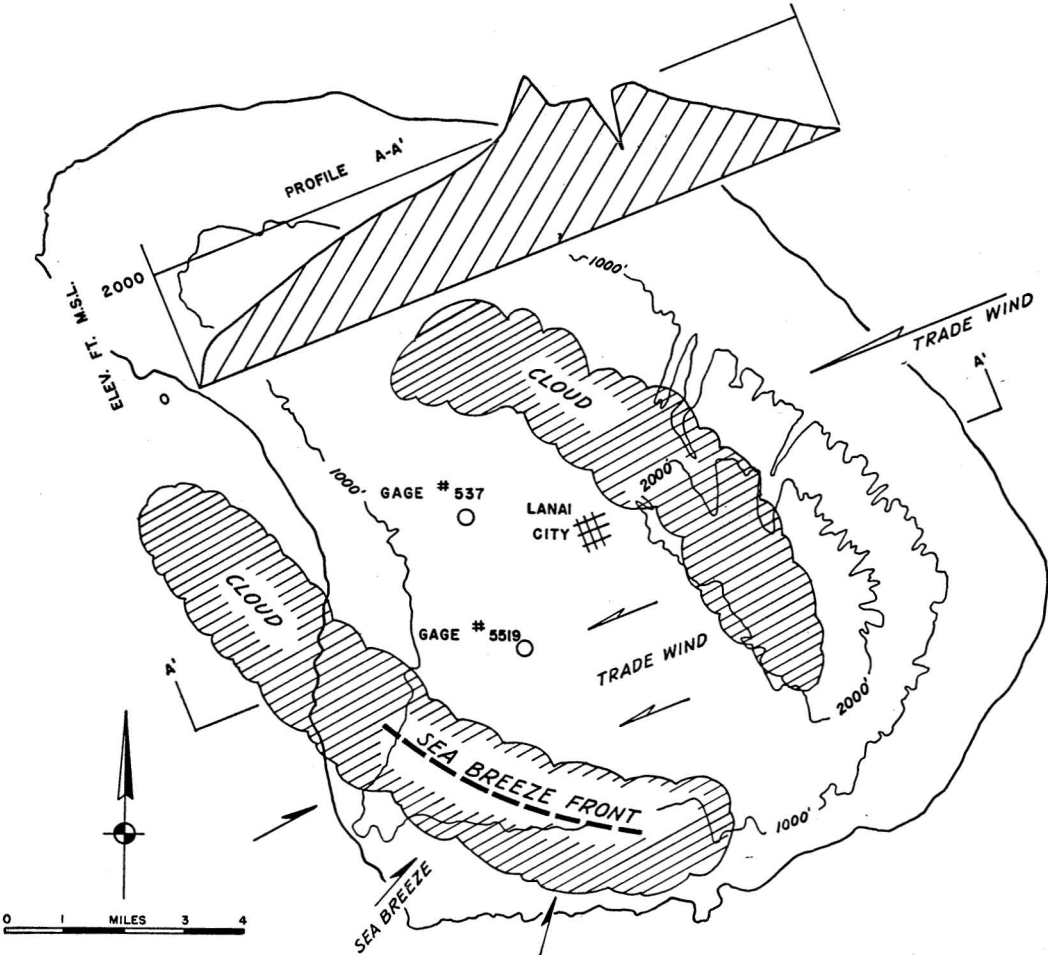


FIG. 2. Map of Lanai showing stations and wind directions.

### *Preparation of Diurnal Rainfall Curves*

Because different synoptic situations are related to these rainfall types, separation of geographical areas over which these types occur is of some interest. In order to make such separation, diurnal rainfall curves were prepared from recording rain-gage records for six of the stations on Oahu and the two stations on Lanai. These recording gages, with the exception of that at Honolulu, were installed by the U. S. Soil Conservation Service about 1941, and are maintained by the sugar and pineapple plantations.

Certain lapses in record made it impossible to analyze exactly the same record period at all gages, but in general, the period January 1, 1945, to December 31, 1946, was used in all cases except Honolulu. The Honolulu quantities had been counted and tabulated for the period 1923 to 1941 by H. P. Parker of the U. S. Weather Bureau, who kindly allowed the writer to use some of his tabulations for this analysis.

From the original recorder charts, the rainfall amounts for stations other than Honolulu were tabulated hour by hour for the period of record. No attempt was made to adjust the chart total to the total recorded in the standard rain gage which, in most installations, is set up adjacent to the recorder. It became apparent at an early stage that a short period of record at gages in dry localities would not yield statistically significant results comparing number of occurrences of various amounts of rain in individual hours. Therefore, all individual occurrences in a given hour were lumped, regardless of amount of rain which fell during the hour. "Traces" of rain do not show up on a Ferguson reconnaissance type gage, so the minimum amount which was counted as an occurrence was 0.01 inch. A seasonal breakdown was chosen of four periods of 3 months each, starting with December, January, and February as the winter period.

It was desired to determine whether there

was a significant difference in rain occurrence at various parts of the day. In Figure 3A is the histogram of rainfall occurrence for individual hours at Kawaihapai. This station has a mean annual rainfall of less than 30 inches. The total number of rainfall occurrences in the 6 winter months of the analyzed record (December, January, and February for 2 years) was 110. It can be seen that the small number of occurrences necessitated grouping to bring out significant differences between various times of day.

For each seasonal group the number of occurrences was computed for all combinations of 8 consecutive hours, i.e., 0000<sup>2</sup> to 0800, 0100 to 0900, etc. For purposes of statistical analysis, the day was broken into three 8-hour periods, one of which provided the maximum number of occurrences in any 8-hour combination. The graphs in Figure 3B show the resulting breakdown for Kawaihapai. The data in Figure 3B are the same as in Figure 3A, merely grouped into 8-hour totals.

### *Statistical Test for Significance*

To determine whether the maximum number of occurrences in an 8-hour period was significantly different from the number in the other periods, a chi-square test was used. Assuming that the three 8-hour periods had equal chance of rain occurrence, the chi-square computation determined the number of occurrences which might occur in 8 consecutive hours once in 100 times as a result of pure chance, and again once in 20 times. If a significantly greater number of rain occurrences was noted in a given 8-hour period than might be expected in random trials, then the original hypothesis of equal chance for all hours appears untenable. In such cases we can reasonably assume that a causal factor operates to provide the observed distribution. Obviously the statistical procedure does not tell us whether the period which the data represent was a good sample of a much longer period.

<sup>2</sup> Hour of day in this report is in local standard time (LST). Times are shown on basis of a 24-hour clock, thus 1300 is 1:00 P.M.

## NUMBER OF RAINFALL OCCURRENCES AT VARIOUS HOURS

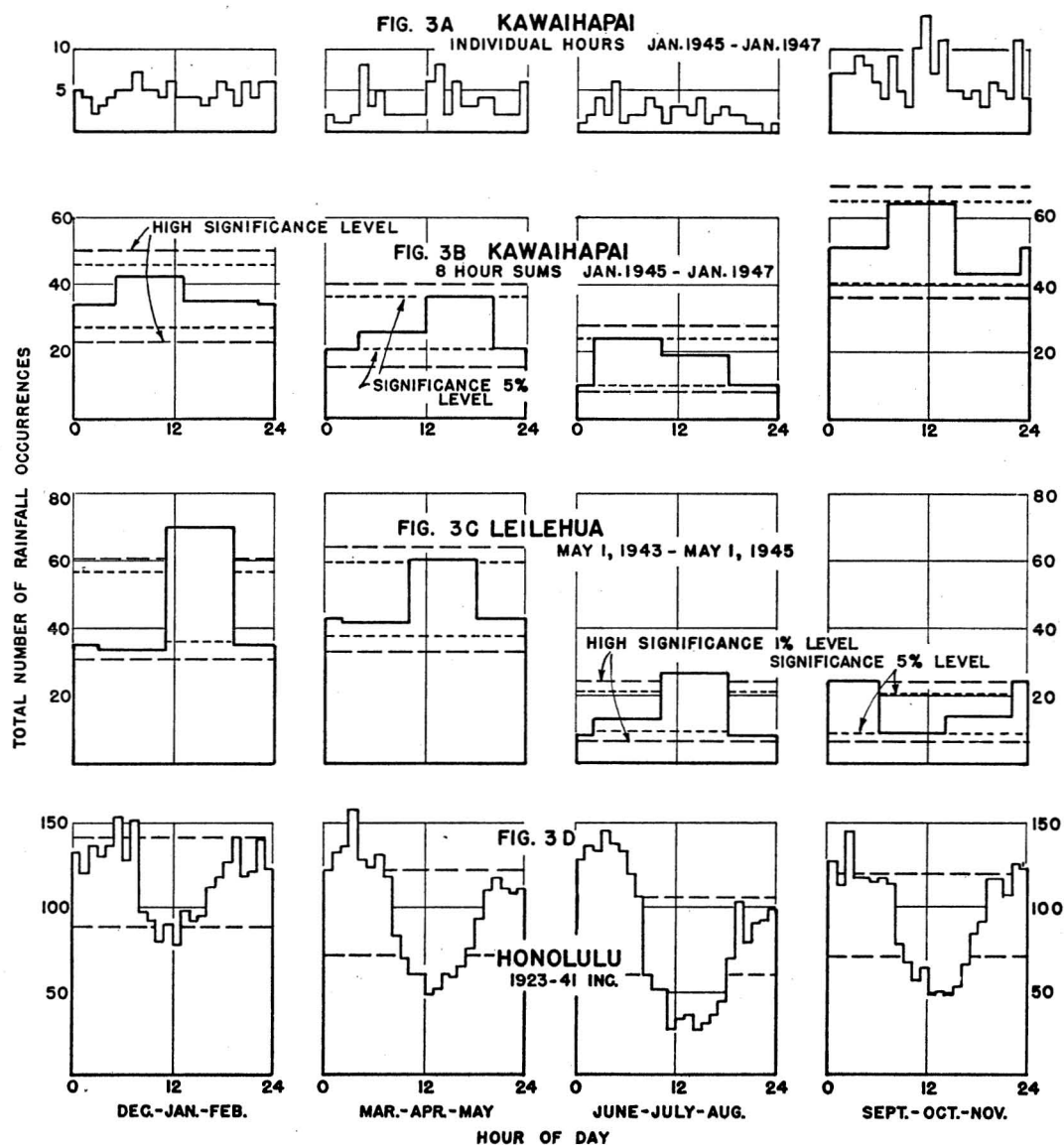


FIG. 3. Number of rainfall occurrences at various hours at three stations on Oahu.

The maximum number of occurrences which might, by pure chance, fall into a time period of 8 consecutive hours is plotted as a long-dashed line in Figure 3B at the ordinate value computed. The minimum number which might fall in an 8-hour group by chance is similarly represented at the computed lower ordinate. In

the same way the number of occurrences expected once in 20 trials is shown by short-dashed lines at appropriate ordinate values. These computed numbers required for significance (adjusted  $X^2 = 3.841$ ) and high significance (adjusted  $X^2 = 6.635$ ) obviously depend in part on the total number of rainfall occur-

rences, and are therefore different for each of the seasonal graphs.

Inspection of Figure 3B shows that no 8-hour period had a significantly low or high number of occurrences in either the winter or fall periods. In spring and summer, the lower significance limits were just reached but no highly significant groups were found.

On the other hand, at Leilehua, Figure 3C, highly significant maxima were reached in the hours 1100 to 1900 in winter, 1000 to 1800 in summer, and 2200 to 0600 in fall. The low significance line was reached in the 1000 to 1800 period in spring. None of the 8-hour groups of Leilehua showed a highly significant minimum number of occurrences.

Comparing the two stations, it appears that Kawaihapai has much more uniform distribution of rainfall occurrences throughout the day than Leilehua. The former shows no consistent

tendency for rain in any part of the day. Leilehua, however, has a strong and significant tendency to receive a maximum number of rainfall occurrences in the afternoon during all seasons except fall.

The other stations were analyzed in a similar manner, and the results are summarized in the following table. In explanation of Table 1, Kawaihoa Girls' School, for example, showed a highly significant rainfall maximum between the hours of 2300 and 0700 in spring. At that season a highly significant deficiency of rainfall occurred between the hours of 1500 and 2300. In summer a rainfall maximum occurred between the hours of 2200 and 0600, while no 8-hour period showed a highly significant deficiency. Winter and fall had no 8-hour periods which showed a large enough or a small enough number of rain occurrences to reach the high significance limits.

TABLE 1. HOURS OF RAINFALL MAXIMUM AND MINIMUM AT VARIOUS STATIONS

STATION	DISTANCE FROM CREST	ELEVATION OF CREST	ELEVATION OF STATION	HOURS OF HIGHLY SIGNIFICANT NUMBER OF RAIN OCCURRENCES				
				Rain occurrences	Winter	Spring	Summer	Fall
Kawaihoa Girls' School	miles	feet	feet					
	3.0*	3,000	300	{Maximum number Minimum number	None None	2300-0700 1500-2300	2200-0600 None	None None
Waimea	4.4	1,000	360	{Maximum number Minimum number	None None	2100-0500 1300-2100	2100-0500 0500-1300	2200-0600 None
Honolulu	5.2	2,500	50	{Maximum number Minimum number	0000-0800 0800-1600	0000-0800 0800-1600	0000-0800 0800-1600	2300-0700 0700-1500
Opaeula No. 8	6.0	1,800	690	{Maximum number Minimum number	2300-0700 None	None None	2300-0700 None	None None
Leilehua	10.7†	2,800	920	{Maximum number Minimum number	1100-1900 None	None None	1000-1800 None	2200-0600 None
Kawaihapai	13.3†	1,000	200	{Maximum number Minimum number	None None	None None	None None	None None
No. 537 Lanai	2.7	2,000	1,450	{Maximum number Minimum number	None None	None None	1400-2200 0600-1400	0900-1700 None
No. 5519 Lanai	3.7	2,750	1,350	{Maximum number Minimum number	None 1600-2400	1000-1800 None	1100-1900 1900-0300	0400-1200 None

\* On windward side of Koolau Range.

† Situated 2 to 3 miles windward of Waianae Range.

In addition to showing the breakdown of highly significant 8-hour periods given in Table 1, the Honolulu record was sufficiently long to show significance in individual hours. Figure 3D shows the occurrences hour by hour for Honolulu. This provides a somewhat more complete picture of the diurnal curve of rainfall occurrence for a station receiving predominantly trade-wind orographic or nocturnal rain.

At appropriate ordinate values a long-dashed line shows the number of occurrences necessary in an individual hour for high significance. That is, if we assume all hours have an equal chance for rainfall, there is less than one chance in 100 that random drawing would provide an individual hour with a larger number of occurrences. Similarly, the lower dashed line shows the lowest number an individual hour should receive in 100 trials of random drawing.

#### *Comparison of Diurnal Rainfall Curves at Various Stations*

It is evident that certain stations have a rainfall maximum during the night, which is generally associated with a minimum in the afternoon. Stations having nocturnal maxima are Honolulu, Kawaihoa Girls' School, Waimea, and Opaepa No. 8. The opposite case is a maximum in the afternoon and a minimum during nighttime hours. This group includes No. 537 Lanai, and Leilehua. Kawaihapai has no significant difference between hours. No. 5519 Lanai shows an afternoon maximum in spring and summer.

The four Oahu gages which lie near the Koolau Range, including Kawaihoa Girls' School on the windward side, show nocturnal maxima. The two gages at some distance from the Koolau Range—that is, Leilehua and Kawaihapai—showed either no significant difference between hours or an afternoon maximum.

The difference is the dominance of orographic rain from the trade winds as against convective showers. The latter are an afternoon phenomenon while trade-wind orographic precipitation occurs primarily at night.

Lanai, as an island, is much drier than Oahu and shows other peculiarities due to the fact that it is partly in the rain shadow of the much higher island of Maui. Both recording gages on Lanai have afternoon rainfall maxima. Though they are relatively close to the mountains, which are just upwind, apparently the overall rainfall deficiency on Lanai due to the rain-shadow effect diminishes the importance of orographic trade-wind showers. Opaepa No. 8 lies twice as far from the mountain crest as the Lanai gages, yet still shows nocturnal maxima. It will be noted, however, that Opaepa No. 8 had no highly significant hours of rainfall minima. This should probably be interpreted as an indication of diminishing importance of orographic rains owing to the distance from the crest.

Again, Leilehua lies only 2 miles upwind of the crest along the central mass of the Waianae Range. The station nevertheless shows predominantly afternoon rainfall maxima. Kawaihapai lies some distance downwind of the lower northerly nose of the Koolau Range. It is 2.7 miles upwind of an 1,800 foot crest of the Waianae Range. Lack of highly significant periods of rainfall indicates the mixed effect of orographic and oceanic rain with convective showers. The explanation might lie in the few total occurrences of rain, but this was tested by increasing the length of record and the results still gave no significant hours.

The diurnal rainfall characteristics of Leilehua and the Lanai gages emphasize the importance of the desiccation of air by the barrier over which the air is forced to rise. The elevation of the band of maximum rainfall on East Maui and on the volcanoes of Hawaii clearly demonstrates this principle. Yet the dominance of afternoon or convective rainfall even at the base of the windward slopes of the Waianae Range and so close to leeward of the Lanai Range is a little surprising.

The statistical results presented above from the limited number of recording rain gages are borne out by the experience of many observers.



### WIND DIRECTION

The diurnal wind patterns for Oahu and Lanai are shown in simplified form geographically in Figures 1 and 2. The full arrows show the normal daytime surface wind direction, and the dotted arrows the night winds. The regime at Waianae is from non-instrumental observations only, but the wind changes shown on the map for other places are all established by recording wind vanes.

The locations of good records of wind direction are unfortunately distributed. A plethora of records exists in the Honolulu-Pearl Harbor area, though space does not allow all locations to be shown on the map of Figure 1. The data clearly establish the fact that there is usually no diurnal change in wind direction in the Honolulu area. This is true also at Aiea and Pearl Harbor. Yet only a short distance away at Waipahu a northwest night wind clearly shows up as the usual thing.

All stations in the southern part of Oahu have a southerly afternoon sea breeze when the large-scale pressure gradient is weak and wind speeds low. These conditions characterize what is locally called "kona weather" on Oahu, when a general tendency for light southerly wind persists.

Kaneohe, on the windward side of Oahu, shows no diurnal change in wind direction. Wheeler Field has the most variable wind, but during the day it is usually northeasterly, and in the night, northwesterly, north, or sometimes southerly. Waianae has a very definite afternoon sea breeze sufficiently strong on most days to give a westerly onshore wind, in direct opposition to the tendency for a trade wind.

It appears that sea-valley and land-mountain winds affect the wind direction over most of the westerly third of Oahu. Complete reversal of wind direction occurs only on the protected lee coast which lies down-trade wind of both the two mountain ranges. A nocturnal land-mountain wind prevails both at Waipahu and Waialua.

A definite sea-breeze front can be found even on the small island of Lanai nearly every summer day. Owing to the low mountain range and the generally dry weather, little vegetation grows on the lower parts of Lanai. The leeward plateau is nearly completely planted to pineapple. This gives rise to strong surface heating and results in a well-marked sea-breeze regime. The map in Figure 2 shows the daytime wind directions and the mean position of a standing sea-breeze front. Directly above this front is a daytime cloud which can be seen on many an afternoon, its position moving a little from day to day depending on the strength of the sea breeze. This cloud is certainly the result of rising air above the place where the sea and trade winds meet. A similar cloud line above the meeting place of sea and trade winds is characteristic of West Molokai.

The diurnal rainfall regime directly related to wind patterns is very clear on the big island of Hawaii. Along the Hamakua coast of the windward or northeast side of the island, there is a definite mountain wind at night from the west, and in early morning a small cloud bank parallels the coast just offshore. The writer has noted the sea breeze begin at 1100 at the elevation of 4,000 feet near Umikoa, and with this wind clouds blow in from the coast and rain begins about noon. The rain or drizzle ends in the late afternoon and it clears up about night-fall, remaining clear at Umikoa all night. The same phenomenon was noted by Dutton (1883) in the Kona districts of Hawaii.

### SURFACE WIND SPEEDS

Average diurnal curves of wind speed for various stations are presented in Figure 4. Kaneohe Naval Air Station is located on a peninsula projecting windward from the island mass, and approximately represents conditions over the open ocean to the windward of the islands. It is apparent that all stations show a maximum wind speed in the afternoon, but the island stations show slightly lower maximum



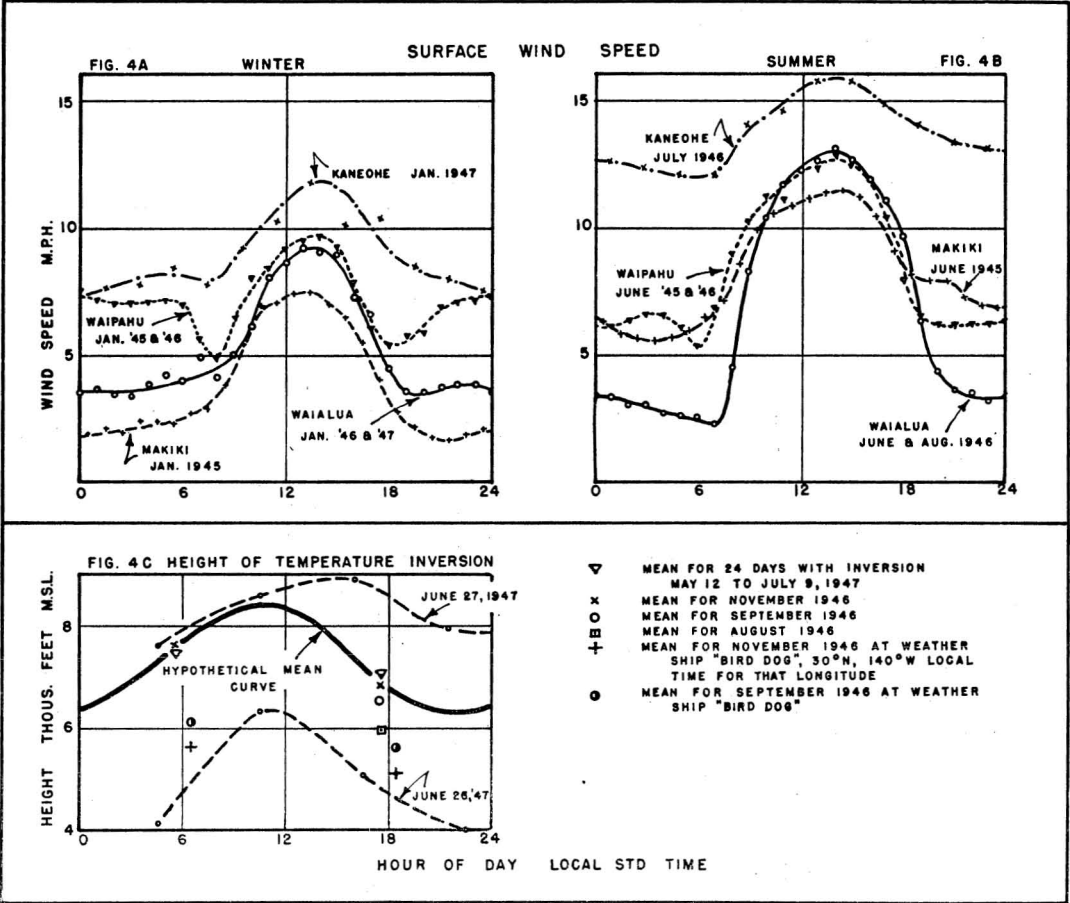


FIG. 4. Diurnal changes of surface wind speed and of the height of the temperature inversion.

speeds than the open ocean (Kaneohe). The night winds at island stations are of much lower speed. It is quite clear, therefore, that the strong diurnal change in wind experienced by island stations is the result of a nocturnal reduction in speed relative to that over the open ocean.

At Waialua the daytime wind is of moderate speed from the east-northeast. The nocturnal wind is light and from the southeast. The vector which must be added to the trade wind to produce the observed night velocity is from the southwest or from the Waianae Range.

At Waipahu the northwest night wind must be caused by a vector from the west added to

the trade wind. This westerly component again comes from the direction of the Waianae Range.

Honolulu experiences no diurnal change in direction but lower speeds at night than during the day. A sea-breeze component would tend to reduce the daytime wind speed while a land breeze should increase the nighttime speeds. Therefore, the real winds must be still greater during the day and less at night than the observed winds.

Part of the diurnal speed changes at Kaneohe must be due to sea-land-breeze effects which would tend to produce the observed winds, with greater speeds during the day than at night.

Surface friction would account for the slightly

lower daytime speeds over the land than over the ocean (Kaneohe).

These observations indicate that the diurnal speed changes cannot be attributed to the sea-land-breeze regime alone. The effect of sea-valley and land-mountain winds is apparently strongest in the vicinity of the Waianae Range. This is particularly apparent by the comparison of Waipahu and Aiea. Part of the explanation probably lies in the fact that the Waianae Range, in the rain shadow and much drier than the Koolau Range, is covered in its lower reaches by a more sparse and xerophytic vegetation cover than are the moist foothills of the Koolau. This could give rise to greater heating and cooling effects on the lower layers of air.

The higher wind speed during the day is ordinarily attributed to transfer of momentum from higher wind speeds aloft to lower levels through increased daytime mixing as a result of greater instability. In the case of the island stations, a very stable layer is produced at night immediately above the ground surface as a result of radiative heat loss. The development of a nocturnal surface temperature inversion is apparent in many individual Honolulu soundings<sup>3</sup> and shows up in the mean sounding for January presented in Figure 5. Obviously this near-surface stability will be much more pronounced over land than over water, and explains the large reduction of nocturnal speeds over the land.

The depth of the layer of low nocturnal speeds also points to stability as the explanation. Figure 6 shows the wind speeds at the four pibal

or rawin<sup>4</sup> scheduled times at Honolulu. It is apparent that the diurnal change aloft is smaller but in opposite phase to that of surface wind. The mean thickness of the ground inversion is roughly the same as the depth through which the large diurnal wind-speed changes occur.

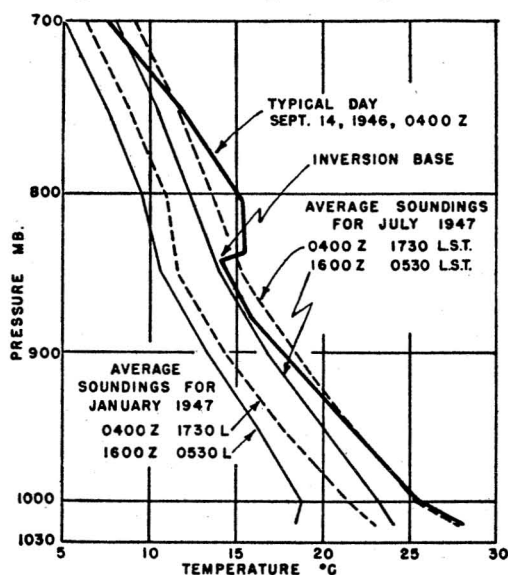


FIG. 5. Soundings above Honolulu.

Since the strong diurnal change in speed is measured at all stations, even at Wheeler Field (elevation 850 feet), and is observed at still higher localities in central Oahu, it appears that the nighttime speed reduction is a near-surface phenomenon. It must occur in a layer somewhat less than 500 feet thick, just above the general land surface regardless of the topography. Insufficient observations are available to determine whether this is true for mountain crests.

<sup>3</sup> A sounding is a measurement of pressure, temperature, and relative humidity aloft. It is plotted in the form of a graph of temperature vs. pressure as in Figure 5. Relative humidity at various pressures is usually entered on the graph. A sounding is taken by release of a small radio transmitter (radiosonde) carried aloft by a balloon filled with helium. Signals indicating the three types of measurements are transmitted by the radio and picked up by a radio receiver on the ground. The words "radiosonde observation" are sometimes abbreviated to "raob." Such observations are made twice daily by the Weather Bureau at Honolulu.

<sup>4</sup> "Pibal" is the abbreviation for pilot balloon. "Rawin" means upper wind observations by means of radar. In each case, a balloon filled with helium is released, rising at a constant rate. Its position in space is tracked by observing it from the ground, through a telescope in the case of a pilot balloon, or by a radar set in case of a rawin. By plotting its position at evenly spaced time intervals, the movement can be computed and thus the wind speed and direction at each level can be determined. Upper air winds are measured four times each day by the Weather Bureau at Honolulu, twice by pilot balloon (visual tracking of the balloon), and twice by rawin.

### THE TEMPERATURE INVERSION AND ITS DIURNAL CHANGE

As an example of a summertime sounding, the September 14, 1946, radiosonde flight of 1730 LST (0400 Greenwich time) is plotted in Figure 5. The base of the subsidence inversion, marked on the graph, was at an elevation of 5,380 feet above mean sea level. The temperature increased  $1.6^{\circ}\text{C}$ . through the inversion which is exactly the mean magnitude for 44 soundings in the summer of 1947. Together with the accompanying rapid decrease in moisture at or near the same level, the inversion is apparently quite sufficient to limit the top of trade-wind clouds. Although direct correlation of cloud tops with the temperature inversion has not been made locally by means of airplane-meteorograph soundings, it is common observation that the low-cloud tops in the area are at quite a uniform level over the ocean even when they are cumuliform in character. Moreover, the

writer's own observations indicate that the height of cloud tops over the mountains is not much different than the general level of the cloud tops over the open ocean. The writer made a rough check with crude thermometers on the slope of Haleakala, the 10,000-foot mountain of East Maui. On the road to the summit, an inversion of temperature of  $3^{\circ}\text{C}$ . was easily distinguished, and it represented very closely indeed the cloud tops prevailing at the time.

Until more careful measurements are made, it may be assumed that, as in the well-authenticated situation in Southern California (Neiburger, Beer, and Leopold, 1945), the temperature inversion is the top of the low cloud deck, and that the additional height of orographic clouds over the mountains is not of a large magnitude.

The co-operation of the U. S. Weather Bureau was solicited to obtain additional upper air data by special radiosonde flights. During a 2-day period, June 26 and 27, 1947, four extra flights were made, which, in addition to the regularly scheduled radiosondes, provided one ascent every 6 hours. The heights of isotherms and the inversion for the 2 days of special ascents are shown in Figure 7 plotted as a time-height cross section. On these particular days the subsidence inversion did not continue unbroken through the night, but as shown to be common in Southern California, disappeared at one level and reformed nearly simultaneously at another. The nearly isothermal layer at 7,500 feet, 1800 LST June 26, already indicated the beginning of the inversion which was well established at 7,700 feet at 0530 the following day. On the 26th the inversion base reached its maximum height at 1030, and on the 27th at about 1500.

The height of the inversion base for these 2 days has been replotted on Figure 4C. The mean heights of the inversion base for the months of August, September, and November, 1946, are plotted on the same Figure 4C at scheduled radiosonde times, 0530 and 1730 LST.

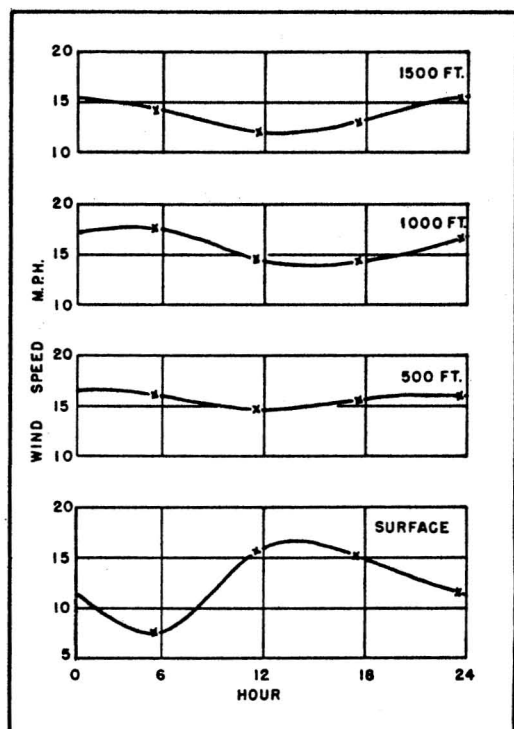


FIG. 6. Wind speed at Honolulu—surface and aloft. Averages from pilot balloons for August, 1946.

Unfortunately, two soundings a day were not flown during 1946 until November. The mean heights for a period during the summer of 1947 are also plotted.

Using the average inversion heights at scheduled radiosonde times at Honolulu, the times of maximum and minimum heights for the 2 days of special observations can be used to approximate a mean diurnal curve of inversion height which has been drawn on Figure 4C.

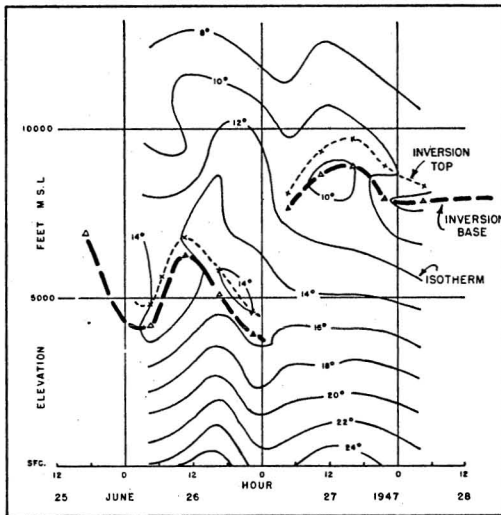


FIG. 7. Time-height section above Honolulu Airport, June 25 to 28, 1947.

The heights of the inversion at the weather ship "Bird Dog" (lat. 30°N., long. 140°W.) indicate a gradual slope upward to the west from California to Honolulu, as was noted by Von Ficker (1937) for the Atlantic and discussed by Neiburger (1945). Using the data on inversion height at Los Angeles collected by the California Stratus Investigation of 1944 (Neiburger, Beer, and Leopold, 1945), the mean slope from California to ship "Bird Dog," a distance of 1,250 miles, is 1/1600. From "Bird Dog" to Honolulu, a distance of 1,300 miles, the slope is 1/3100. These slopes corroborate well the estimate made by Neiburger and check Von Ficker's measurements over the Atlantic.

The stratus ship just off the coast at Los Angeles showed the inversion base to have its maximum height about 0630 local standard

time for that longitude, and minimum about 1300. The weather ship "Bird Dog" showed a mean height of the inversion base higher at 0630 than at 1830, the local times of her radiosonde flights. Without intermediate soundings, it is impossible to estimate exactly when the maximum and minimum occur at that location. The hypothetical mean curve for Honolulu indicates that the maximum height occurs about 1100 LST and the minimum about 2200. Since a radiosonde released at the Weather Bureau Station at the Honolulu Airport drifts west-southwest with the trade wind over the ocean during its entire flight, the sounding represents lee-side conditions more oceanic than insular. A general check on a daytime maximum inversion height is provided by observations of Powers and Wentworth (1941) on the slopes of Mauna Kea. From Pohakuloa, above the cloud deck, they noted a daytime increase in the height of the cloud top, which receded to lower levels at night.

The diurnal variation in the height of the temperature inversion was attributed by Neiburger (1944, 1945) primarily to the result of sea-land-breeze effects together with lesser effects of advection and surface heating. He postulated that the sea breeze increased the wind speed over the coast causing the inversion over the coastline to lower during the day, the air escaping inland through the mountain passes. Nighttime land-mountain breezes flowing toward the ocean caused the inversion gradually to rise during the night. This explanation fits less well the conditions over Honolulu than Los Angeles. First, the sea and land breeze does not appear to be stronger than on the coast of the continental land mass. The island is small, and its opposite sides lie within short horizontal distances. Yet there are no direct indications of large variations in the inversion over these short distances. Second, the inversion is considerably higher over Honolulu than over California, which would tend to minimize the diurnal height changes resulting from sea-land-

breeze effects. Yet the magnitude of the diurnal change in height, admitting a very incomplete record at Honolulu, appears to be greater at Honolulu than at Los Angeles. Third, the difference in inversion height between scheduled radiosonde times at the ship "Bird Dog" is greater than that for the west coast and less than the difference at Honolulu. It is in the same phase as that at Honolulu. These heights and those of California stations are summarized in the following table.

Thus it appears from limited data that the diurnal curve of the temperature inversion does not fit easily into the explanation which appears reasonable for the California coast. There is apparently a diurnal change in height over the open ocean, felt by near-coast and insular locations, which is not explained by sea-land-breeze effects.

The same kinds of diurnal temperature changes in the atmosphere aloft above the inversion were noted at Honolulu as were described for California (Leopold and Beer, 1947), i.e., an appreciable warming during the daytime. There is still some question whether this measured diurnal temperature change in the free air aloft is real or whether insolation heating of the radiosonde provides an appreciable por-

tion of the increase. If these cyclical temperature changes prove to be real, they might indicate a diurnal cycle of vertical motion quite unrelated to sea-land-breeze effects which would affect the height of the inversion.

#### RELATION BETWEEN VARIOUS DIURNAL PHENOMENA

Loveridge's (1924) curves for the diurnal variation of rainfall for Honolulu, 1905-23, are well verified by Parker's tabulations (see p. 84) for the same stations for 1923-41. The occurrence of trade-wind rains primarily at night has been discussed by Loveridge (1924) and Jones (1939). The former noted the out-of-phase relation of surface wind speed at Honolulu and the rainfall. With the night wind speed explained by stability in the lower layers, the question is raised concerning the relation of rainfall to the temperature inversion. It might be argued that the lower cloud tops at night which should accompany a lower nighttime inversion would reduce the tendency for precipitation at the same hours. The effect of cloud height alone is probably minimized by the fact that none of the clouds providing the trade-wind rain reach into freezing temperatures.

Wind speeds aloft actually increase some-

TABLE 2. DIURNAL CHANGES OF TEMPERATURE INVERSION—LOS ANGELES TO HONOLULU

	SAN CLEMENTE ISLAND	STRATUS SHIP	U.C.L.A.	SANTA ANA	SHIP "BIRD DOG"	HONOLULU
Miles from local coast	60 off shore	10 off shore	5 inland	8 inland		0
Maximum height in feet . . . . .	2,300	1,600	1,850	1,600		8,400
Minimum height in feet . . . . .	1,700	1,100	1,200	750		6,300
Time of maximum height . . . . .	0630	0630	1100	0800		1100
Time of minimum height . . . . .	1130	1300	2200	1930		2200
Difference in height 0530-1730 LST feet	300	400	200	650	550* 540†	700

\* Ship "Bird Dog" data for November, 1946; † "Bird Dog" for September, 1946.

Notes: Honolulu data for November, 1946, and May-June, 1947.

California data for "ship period," 2 weeks in September, 1944.

Times are local standard for respective longitudes.

what at night and are directly out of phase with inversion heights, as can be seen by comparison of Figure 4C and Figure 6. Though the average increase is small, it appeared in September data as well as in the August data presented in the figure. That these changes of wind speed are related to the lower inversion at night is indicated by a simple calculation of hydraulics. Using the shape of the curve of Figure 4C and the plotted points showing mean heights of the inversion base for individual months, the maximum and minimum heights of the inversion were estimated for August and September, 1946. The diurnal curves of wind speed at various levels aloft presented in Figure 6 for August, 1946, were similarly computed for September, 1946.

Assuming no compression, the mean wind speed below the inversion should increase as the inversion decreases in height if energy is to be conserved. The ratio of wind speeds should be the same as the ratio of inversion heights if the inversion is a surface through which parcels of air do not pass. Table 3 presents these ratios.

The diurnal curves of wind speed could not be drawn for elevations above 2,000 feet because clouds limited the height of pilot-balloon observations. Nevertheless, the ratios are sufficiently close, considering the limitations of the data, to indicate that the diurnal variations of wind speeds aloft are the result of diurnal changes of inversion height as would be expected from theoretical considerations.

Loveridge (1924) and Jones (1939) attribute the nocturnal rainfall at Honolulu to the radiative cooling at the top of the clouds.

Soundings from Honolulu Airport are too far from the mountain crest to be representative of conditions in the orographic clouds. However, some nocturnal cooling at all levels seen in the Honolulu soundings is probably also true over the mountains with additional cooling near cloud tops. Cooling at all levels implies a lower lifting condensation level or a lower cloud base at night than in the daytime. This is verified by observation. Higher nocturnal wind speeds aloft probably mean more turbulence and larger droplet size. All these factors would tend to provide a nocturnal maximum of rainfall.

In so far as the city of Honolulu is concerned, many rain showers result from the blowing of rain droplets considerably leeward of the edge of the cloud producing them. Higher wind speeds would again tend to a nocturnal rainfall maximum in the city.

#### SUMMARY

The importance of convective shower activity in areas leeward of the main zone of orographic rainfall has not hitherto been brought out. Afternoon maxima of rainfall are observed in the center of the leeward plateau of Lanai and along the west edge of the Wahiawa saddle of Oahu. This implies that convective showers are an important source of moisture in many of the drier parts of the islands where only a moderate part of the moisture has been dropped from the air as a result of prior orographic lifting. It is likely that too much moisture has been extracted to give many local convective showers in the Lualualei area, though no gages were available there for analysis. Such areas must depend on

TABLE 3. RATIOS OF MAXIMUM/MINIMUM INVERSION HEIGHTS AND RATIOS OF WIND SPEEDS, HONOLULU

PERIOD	MAXIMUM AND MINIMUM INVERSION HEIGHT IN FEET	RATIO MAXIMUM/ MINIMUM INVERSION HEIGHT	RATIO OF MAXIMUM/ MINIMUM WIND SPEEDS AVERAGE 500-2,000 FEET
August, 1946 . . . .	{ 7,500 5,400 }	1.39	1.23
September, 1946 . . .	{ 8,000 6,000 }	1.33	1.44



the less frequent kona storms for important sources of rainfall.

The subsidence inversion of temperature occurs at higher elevations over Honolulu than over Los Angeles. The inversion has a diurnal change in height similar to certain coastal stations in Southern California. The local sea breeze shows up only on the lee or well-protected parts of Oahu and Lanai. Because of the small size of the islands and the considerable height of the inversion, diurnal changes in this height as a result of convergence in the sea breeze seem a less likely explanation for Honolulu than for Los Angeles.

Diurnal changes in surface wind speeds are consistent over the islands. The nocturnal speeds are very much less than those over the open ocean. This is apparently explained quite adequately by nocturnal stability in the lower layers.

Wind speeds aloft increase slightly at night and the magnitude of this increase corresponds to that which would be expected by the changes in height of the inversion.

#### REFERENCES

- DUTTON, C. E. 1883. Hawaiian volcanoes. *U. S. Geol. Survey, Ann. Rpt.* 81-219.
- JONES, S. B. 1939. The weather element in Hawaiian climate. *Assoc. Amer. Geog., Ann.* 29: 29-57.
- LEOPOLD, L. B., and C. G. P. BEER. 1947. The coastal sea breeze in relation to diurnal temperature changes in the lower atmosphere. *Amer. Met. Soc., Bul.* 28 (8): 371-380.
- LOVERIDGE, E. H. 1924. Diurnal variations of precipitation at Honolulu. *U. S. Monthly Weather Rev.* 52: 584-585.
- NAKAMURA, W. T. 1933. A study of the variations in annual rainfall of Oahu based on the law of probabilities. *U. S. Monthly Weather Rev.* 61: 354-360.
- NEIBURGER, M. 1944. *Temperature changes during formation and dissipation of west coast stratus.* U. S. Weather Bur., Res. Paper 19, Washington.
- C. G. P. BEER, and L. B. LEOPOLD. 1945. *The California stratus investigation of 1944.* 84 p., 35 fig. U. S. Weather Bur., Washington.
- POWERS, W. E., and C. K. WENTWORTH. 1941. Air movements in the Mauna Kea-Mauna Loa saddle, Hawaii. *Amer. Met. Soc., Bul.* 23: 6-13.
- VON FICKER, H. 1937. Die Passatinversion. *Veröffentl. d. Met. Inst., Univ. Berlin*, Bd. 1, Heft 4.
- VOORHEES, J. F. 1929. *A quantitative study of the rainfall of the island of Oahu.* App. A, Sup. to Dept. Honolulu Sewer and Water Comm., Rpt. 293-302. Honolulu.
- WENTWORTH, C. K. 1946. *Geographic variation in annual rainfall on Oahu.* 14 p., 4 fig. Hawaii Univ., Res. Pub. 22. Honolulu.

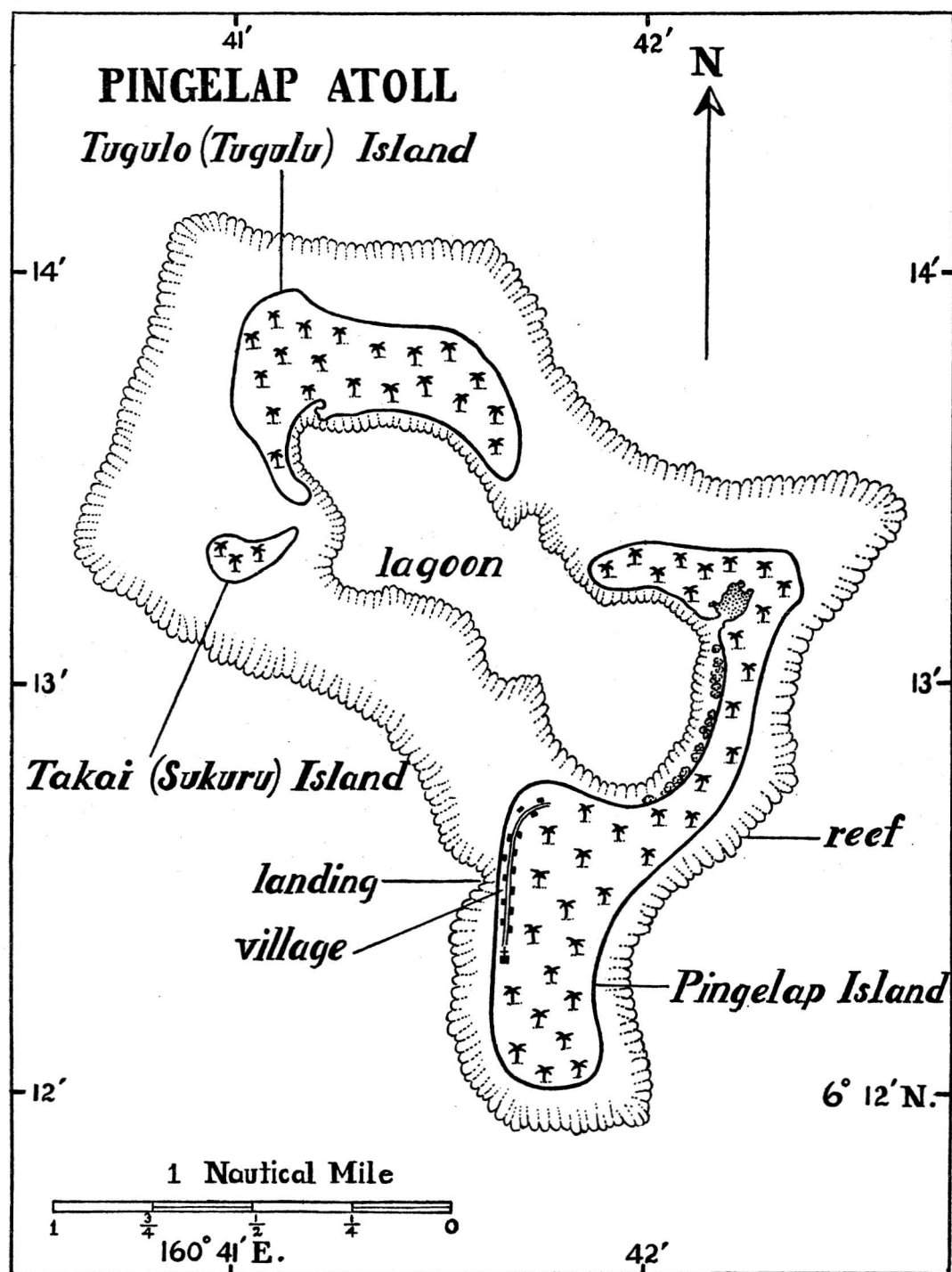


FIG. 1. Map of Pingelap Atoll.