THE INTERACTION OF TRADE WIND AND SEA BREEZE, HAWAII

By Luna B. Leopold

Pineapple Research Institute and Experiment Station, Hawaiian Sugar Planters' Association[1]

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ABSTRACT

Local sea-breeze and land-wind regimes in Hawaii meet and interact with the prevailing trade wind giving rise to cloud lines of distinctive character. These cloud systems are sources of rain and are sufficiently frequent to be important influences in local microclimates. Four different types of interaction are described.

The types of interaction are primarily determined by the height and size of mountain barriers. High barriers may split the trade wind into lateral currents flowing around the mountain while low barriers allow the trade wind air to blow over the top of the mountain.

Measurements of local surface-pressure gradients and pilot-balloon data taken adjacent to the zones of interaction provide bases for a description of the vertical and horizontal circulations set up by the meeting of trade wind and sea breeze.

1. Introduction

Local climates of various portions of islands in the trade-wind belt are sensitively related to the manner in which topographic features alter the trade-wind flow. Orographic lifting is a major determinant of rainfall distribution, not only on days of normal trade wind but also during passages of pressure troughs in the westerly currents aloft. In addition, the obstruction of the trade winds by mountains of various shapes and sizes can cause standing waves in the atmosphere which are associated with distinctive patterns of vertical motion (Queney, 1948; Hess and Wagner, 1948), and can cause lateral splitting of the trade current which results in horizontal convergence and divergence patterns. The flow patterns over islands and coastal areas are in addition complicated by the development of local sea–land and mountain–valley wind regimes which interact with the general trade-wind flow. At least in Hawaii, the cloud and precipitation patterns developed by this interaction are more important than those resulting from the standing pressure waves. These local cloud systems affect local temperatures, humidities, and rainfall, and thus become important determinants of local ecologic habitats.

It is the purpose of this paper to describe the cloud patterns arising from the interaction of trade wind and sea breeze in Hawaii, to examine some local rainfall patterns and to provide explanation of these patterns in terms of the interaction of wind systems and the flow of air over and around the mountain masses.

A general discussion of the manner in which vector components of sea–land winds add to and alter the wind vector of the prevailing wind is given by Garbell (1947, p. 20). Specific examples in the Hawaiian Islands will be examined which illustrate how local patterns may vary from the generalized theoretical case.

At various places in the Hawaiian chain, interaction of trade wind and sea breeze provides four distinct types of cloud patterns and their corresponding rainfall and temperature patterns.

2. The sea-breeze front of Lanai and Molokai

Lanai and Molokai are relatively small compared with other islands of the Hawaiian group. The main mountain ridge on Lanai reaches a maximum elevation of 3300 ft from mean sea level. In its lee with respect to the northeasterly trade wind is a broad plateau at an elevation of about 1000 ft. On this plateau is a pineapple plantation of some 17,000 acres.

Molokai is long and narrow, oriented east–west. Its eastern half is rugged with a maximum elevation of 4900 ft but the western portion consists of a flat ellipsoidal dome, whose maximum elevation is about 1300 ft. Both western Molokai and the Lanai plateau are relatively dry and, exclusive of the arable land which is in pineapple, consist of a heavily grazed savanna with an admixture of exotic cactus. On the southern coastal portions of these areas which are leeward with respect to the trade wind, an onshore sea breeze is generally present from midmorning to midafternoon. On northerly coasts the sea-breeze component onshore merely adds to the trade-wind flow which at the surface reaches maximum speed near midday.

These opposing wind systems during the middle of the day meet each other in a surprisingly narrow zone. On Lanai, for example, the airstrip, which is 3800 ft long (for location see fig. 1), often shows fresh northerly trade wind at one end of the field and fresh southerly sea breeze simultaneously at the other end.

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On six arbitrarily selected days in the summer of 1948, maps of surface wind direction were constructed on Lanai. The observer traveled in a jeep from place to place stopping periodically to measure wind direction with a Brunton compass. Fig. 1 presents sample maps of the space distribution of surface winds mapped in this way. The geographic position of the zone of interaction changes during the day as the strength of the sea breeze increases and wanes. The writer has briefly mentioned this phenomenon previously (Leopold, 1948), and has called the zone of interaction the "sea-breeze front." The front is similar in many respects to that pictured by Koschmieder (see Wexler, 1946, fig. 2) but because of the instability of the semi-tropical air of Hawaii and the strength of the trade winds, it has certain distinctive features which we will examine here.

It is obvious that where two opposing winds meet on such a narrow front there must be a line of vertically rising air, as discussed previously by Wexler. On Lanai and Molokai a long cloud line always lies more or less directly over the sea-breeze front and parallel to it. This cloud, which we will call the "sea-breeze cloud," is usually bounded by areas of clear sky suggesting that on either side of the line of rising air are zones of subsidence, and that there are two long cells of circulation having parallel horizontal axes. In fig. 2, a typical example of the sea-breeze cloud on Lanai is illustrated.

In an attempt to determine the nature of the air circulation in the postulated cells, three types of observations were made on Lanai during the summer of 1948. A line of four instrument shelters was set up (positions are shown on fig. 4) each of which contained a microbarograph, a hygrothermograph, and a recording wind direction instrument. Each of the instruments ran on its own individual eight-day clock. The four observation points were approximately equidistant and oriented in a line approximately parallel to both the surface sea breeze and the trade wind in that portion of the island. The instruments were kept running for about 4½ months and after deducting the various periods in which one or another of the twelve clocks was inoperative, about two months of good record were available. A microbarograph at Lanai City provided an additional station for the pressure analyses.

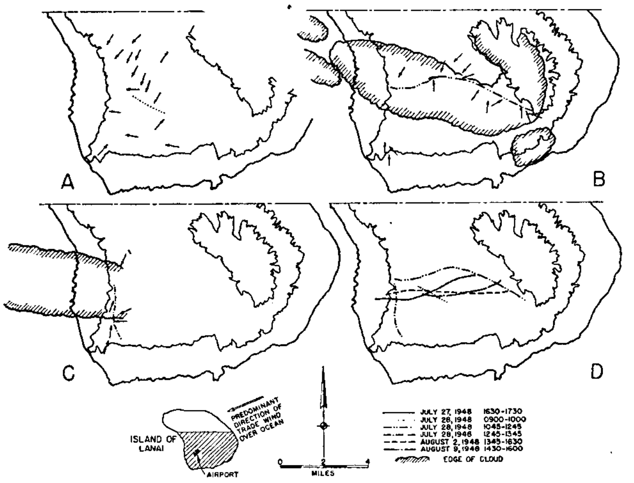

FIG. 1. Surface wind directions (arrows) on southern half of Lanai, 28 July 1948 (A, B, and C) and position of the sea-breeze front on four sample days (D). Maps A, B, and C are for the time intervals 0900–1000, 1100–1200, and 1300–1400 (local time). Contour lines are for 1000 and 2000 ft. In A, the central portion of the island was overcast.

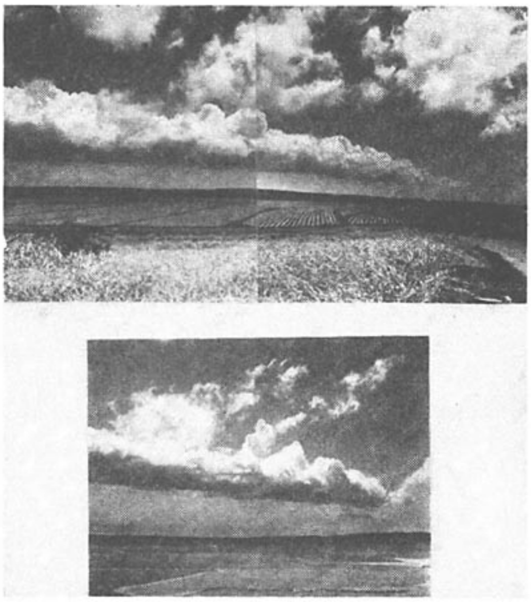

FIG. 2. Cloud line above sea-breeze front on Lanai. The upper photograph looks SW from Lanai City at 1000, 28 July 1948. The lower photograph looks SW from Puualealea, a hill north of Lanai City; note curve of cloud line at far right end of cloud where it is blown seaward by the general NE trade wind.

The second type of data consisted of 49 pilot-balloon observations of upper winds over Lanai, observed from points on each side of the sea-breeze front. In addition 32 balloons were observed on Maui. The third and not the least interesting type of data was a series of rapid motion movies in color in which the camera was triggered by a solenoid timed by a metronome to take one frame every 1¼ sec. In this manner the cloud motion was speeded up so that on the screen one hour of cloud motion could be viewed in about 80 sec. Some 500 ft of such film were finally available after editing.

Diurnal changes of wind direction.—As indicated by the diagrams of Garbell, on that portion of an island where the trade wind meets the sea breeze at an obtuse angle, the resultant wind will gradually change direction during the day as the sea-breeze component increases. The location of station 1 is in such a situation, with the trade from the northeast and the sea breeze, at its maximum strength, from the south. Five months of data were used to construct wind roses for this station, summarized in table 1.

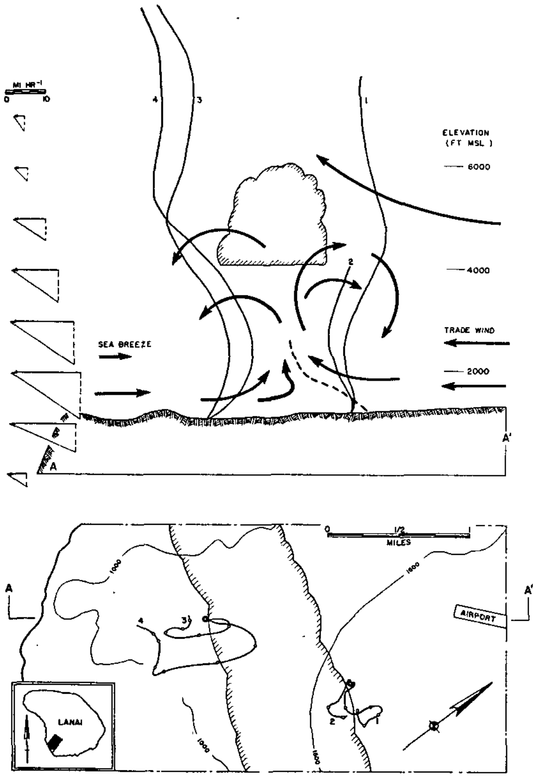

FIG. 3. Upper-air flow in relation to sea-breeze cloud, 0900–1000 10 September 1948, shown in vertical cross section (above) and horizontal projection (below). On the upper drawing the thin solid lines are the projection of the balloon paths and the heavy arrows indicate the deduced circulation pattern. The dashed line shows the sea-breeze front at about 1000. The component of the wind over Honolulu at 0500 along the projection is shown by the arrows at the left. Cloud outlines are shown on both drawings by hatched lines. On the lower drawing, the positions of the balloons at two-minute intervals are shown by the small circles.

The wind is from the trade direction all during the night, at which time there is doubtless some land-wind (offshore) component added to the trade. The first important shift is seen at 0900 when the SE quadrant contains an important percentage of cases. By 1100 the SW quadrant dominates. The shift back to trade direction occurs between 1500 and 1900. On individual days there is a tendency for a clockwise shift during the morning and a counterclockwise turning as the sea breeze wanes in the afternoon, in a fashion similar to that observed by Hann and Süring (1940) at Batavia.

TABLE 1. Mean diurnal wind rose for station 1 on Lanai, 24 May–18 October 1948. Figures are the frequency (per cent) of wind from the indicated directions at the indicated time.

Hour (local time)	N-ENE	E-SSE	S-WSW	W-NNW	Calm
0100	36	3	1	1	59
0300	35	3	2	3	57
0500	34	2	1	4	59
0700	42	10	2	4	42
0900	32	24	20	10	14
1100	20	27	37	14	2
1300	25	18	36	20	1
1500	38	16	25	19	2
1700	68	10	10	10	2
1900	71	11	4	3	11
2100	53	5	4	3	35
2300	41	4	3	2	50

Vertical structure of the sea-breeze cloud.—The movies and the pilot-balloon observations provide some indication of the vertical structure of the circulation cells. The pilot balloons were released both in the zone of the surface sea breeze and in the trade-wind zone. Certain balloons were released from positions chosen so that at the particular time the balloon would rise adjacent to the cloud edge without disappearing in the cloud itself. On 10 September 1948, within a single hour, balloons 1, 2, 3, and 4 (fig. 3) followed such paths. Balloon 1, for example, was released in the sea breeze directly under the north edge of the cloud existing at that time. As can be seen by the vertical projection of its path (upper portion of fig. 3) it passed quickly out of the southerly wind into the trade-wind flow, in which it continued up to 2200 ft msl. where it reversed its path and was blown north. In other words, under the northern edge of the cloud a thin layer of sea breeze lies under trade wind flow. In the layer 2200–4700 ft msl the balloon was in a southerly wind which is interpreted as the upper portion of a circulation cell, the axis of which is horizontal. Above this cell the balloon entered the general trade flow aloft.

Balloon 3 was released in the sea breeze at the surface under the southern edge of the cloud. It continued in that current to an elevation of 2200 ft msl and was then carried southward until it reached 5000 ft msl. At this time the base of the cloud was 3000 ft above the local ground surface or about 4000 ft msl. These balloon paths indicate the correctness of the generalized streamlines shown as heavy arrows in the upper portion of fig. 3. Downward motion on both sides of the cloud can be clearly seen in portions of the movie.

The sea-breeze front in the lowest levels slopes toward the sea air with height in a manner similar to that shown by Koschmieder (fig. 2 of Wexler, 1946). The same direction of slope was observed by noting cloud movements at the sea-breeze front on the Pohakuloa saddle of the island of Hawaii.

It should be noted that balloon 3 encountered a light southerly current between the level of 5000 and 7000 ft msl and balloon 4 showed a lighter but perceptible southerly component between the same levels. This motion does not fit into the main circulation indicated diagrammatically by the heavy arrows of fig. 3. No attempt was made to explain this anomalous motion because in a flight where considerable vertical motions must exist, the assumed heights of the balloon determined only by duration of flight must accumulate error. An indicated height of 5000–6000 ft is liable to be sufficiently erroneous to preclude deduction of details of the circulation at such levels.

To summarize, the pilot balloons, movies, and surface wind maps indicate that in the case of the Lanai-type sea breeze cloud, the surface sea breeze blows in a direction opposite to the surface trade, and the zone of convergence is a narrow line, perpendicular to the winds. Two circulation cells are set up on each side of the interaction zone, and the axes of these cells are horizontal. The top of the cloud is in a divergent zone, and downward motion predominates in the air near the lateral edges of the cloud line. The cloud top is nearly always at the level of the base of the subsidence temperature inversion, which averages between 6000 and 8000 ft msl over the Hawaiian Islands.

Surface pressure gradients.—The pressure gradients between the five microbarograph stations provide further insight into the nature of the air movement. The pressure stations, as mentioned previously, were in a straight line approximately along the direction of the local surface trade-wind flow. Since the stations were at different elevations and because the double diurnal pressure fluctuation was nearly of the same magnitude as the sea-level pressure differences between the stations, the following type of analysis of the pressures was made. Using one summer month during which an unbroken record was available for every station, the mean pressure at each station was computed for each hour, thus obtaining a mean diurnal pressure curve for each station. For each station the arithmetic mean of the 24 hourly-mean values was computed, and the respective deviations of hourly-mean values from the 24-hr mean were then obtained. At any hour the difference in deviation from the respective means provides a measure of the pressure force existing after the differences in elevation of the stations have been eliminated.

The pressure differences between stations have been plotted on fig. 4 in which the slopes of the lines connecting the stations indicate the pressure gradients between them. Such pressure profiles are presented for alternate hours. The most obvious feature of this series of graphs is the onshore gradient from 0900 to 1700 between stations 1 and 3. This onshore sea-breeze gradient is replaced at night with an offshore gradient representing a land breeze.

Since the sea breeze does not often extend inland beyond station 3, and northeasterly trades ordinarily blow from Lanai City toward station 3, the explanation of the pressure gradients between station 3 and Lanai City is not as apparent.

The observed variations of gradient are possibly related to 'Queney waves' caused by air flow over the mountain. It happens that one of the examples of mountain configuration for which the streamlines and surface pressure profile were computed by Queney is a rough approximation of conditions on Lanai. Queney postulated a smoothly contoured mountain ridge perpendicular to a uniform current with a speed of 10 m sec^{-1}. From his diagram (Queney, 1948, p. 19) the cross section of his assumed mountain has been plotted over the actual profile of the island of Lanai in section A–A′ of fig. 4. His theoretical surface-pressure profile has been replotted at the bottom of fig. 4 at the same scale as the Lanai pressure profiles. It can be seen that the pressure profile measured on Lanai which most closely approximates Queney's theoretical pressure profile is that for 0700. It is interesting that this is also an hour of minimum sea–land wind flow.

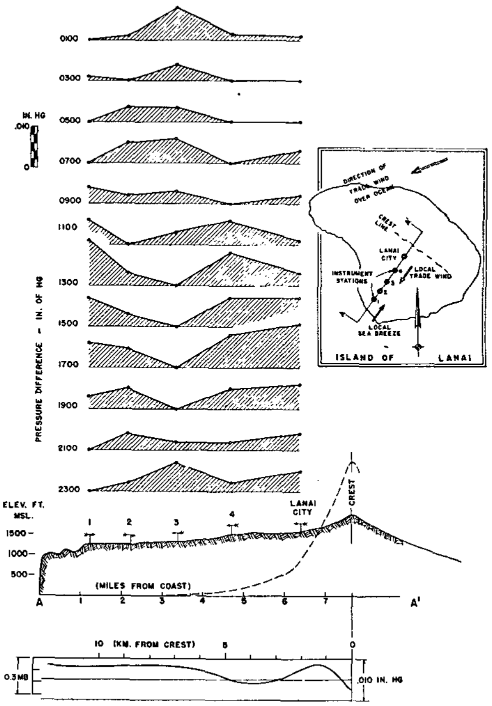

FIG. 4. Mean surface-pressure profiles on Lanai at odd hours, corrected for differences in elevation. In lower part of figure, actual Lanai profile (hatched line) is compared with idealized mountain profile of Queney's (dashed line) for $\alpha = 1$ km and Queney's theoretical pressure profile is plotted on the same scale as the observed mean profiles for Lanai.

However, pressure gradients measured on the windward slope of Lanai during the winter gave anomalous results leaving doubt as to whether Lanai conditions can be compared with the Queney curves. Pressure and cloud observations elsewhere in Hawaii indicate the probable presence of a phenomenon resembling the hydraulic jump, in the air flow over the mountain crests. Further observations are required before definite conclusions can be reached.

Formation of the Lanai-type cloud line.—On each day that the sea-breeze cloud reaches its average size, the cloud line extends a considerable distance out to sea in a direction WSW or W from the island. This is true on both Molokai and Lanai. The movies, particularly, provide an indication of the fact that the offshore clouds were actually formed over the island and

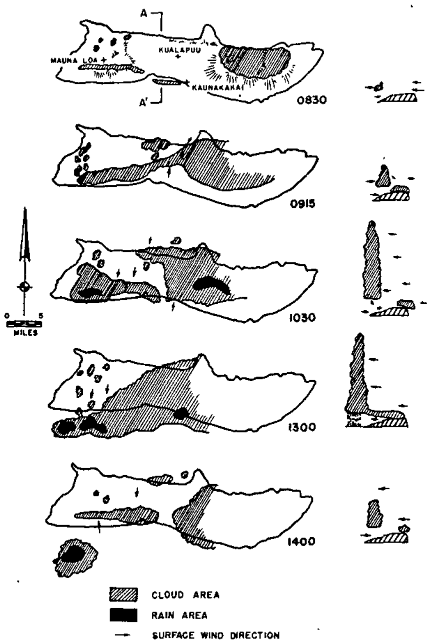

FIG. 5. Diurnal changes in clouds over Molokai, 10 September 1947, showing typical naulu rain shower. Drawings on the right are vertical cross sections through the line A′–A.

blew off in a direction determined by the trade wind at cloud level. The interaction of sea breeze and trade wind over the island is, therefore, a cloud machine which provides continually a source of new clouds as the ones already formed are blown out to sea.

Since a clock appears in the cloud movies, by following individual clouds on the movie a computation of the rate at which clouds are blown off the island is possible. The Molokai cloud photographed from Lanai was found to move at a rate equal to the wind speed shown on the Honolulu pilot balloon at the height of the cloud center, as might be expected.

The naulu rainstorm.—On the islands of Molokai, Lanai, and Maui, the name *naulu*[2] is applied to a type of summertime convective shower which covers small areas of the drier portions of those islands with high intensity and short duration rainfall.

According to the local people, one of the characteristics of the storm so named is that the rain may form over the ocean and blow onshore, or form over the land and blow offshore where it may continue to fall a tantalizingly short distance away from crops in dire need of rain. That the naulu is a product of the sea-breeze cloud became evident when the writer first observed the life history of such a rain on Molokai. The series of events mapped on 10 September 1947 is outlined in fig. 5 and frequent subsequent observations have confirmed the sequence as typical.

Fig. 5 first shows the cloud outlines over Molokai at 0830. A thin line of sea-breeze cloud had appeared over west Molokai while mountainous east Molokai was blanketed on the windward side by a typical orographic cloud mass. By 0915 the width and height of the sea-breeze cloud had increased as shown and considerable vertical development had already been attained.

Surface winds mapped at that hour are indicated on the figure. The sea breeze was separated from the trade wind by a very narrow line of calm. By 1030 rain was falling from the sea-breeze cloud and there was also a shower falling on the lee side of the orographic cloud over east Molokai. By this time the sea-breeze cloud had developed vertically to a maximum height of about 10,000 ft, and was blowing slowly southward under the influence of the general trade wind. At this time, at least in the area under the shadow of the main sea-breeze cloud mass, the sea breeze had stopped and was replaced by trades. This can be attributed in part to the lack of continued ground heating in the cloud shadow and the ground cooling in the rain area.

By 1300 the naulu rain had blown completely offshore to the southwest of the island and most of west Molokai was again in sunshine. By 1400 a sea breeze had been re-established on the south shore and a new sea-breeze cloud was forming above the zone of interaction of the two wind systems.

Naulu rains on Lanai provide a distinctive closed isohyet of higher rainfall on the mean summer rainfall map. This isolated hill or knob in the rainfall pattern lies under the mean position of the sea-breeze front.

3. The Maui type circulation cell

We have seen that the air flow over Lanai consists of two circulation cells whose axes are horizontal. The two major cells are immediately upstream and downstream of the line along which the trade wind meets the sea breeze. Maui represents another type of circulation. Its distinctive character is determined by the fact that the east mountain is in the form of a low-angle cone, the apex of which is sufficiently high to extend well above the temperature subsidence inversion. Below the inversion, the air tends to flow around the cone rather than over it.

Maui consists of two volcanic cones which are connected by a flat low isthmus. The easterly cone, Haleakala, reaches to 10,000 ft, nearly twice the height of the one on west Maui. The maximum annual rainfall zone (about 400 inches) on the northeast exposures of Haleakala is at an elevation of about 3000 ft, above which the rainfall decreases to 20 inches at the summit. West Maui, on the other hand, experiences increasing rainfall to a maximum near the extreme summit, at an elevation of 5000 ft. This difference in

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[2] The word is pronounced "nów-loo," though the phonetic spelling cannot convey the softness with which an Hawaiian stresses all letters equally. Local linguists say that the word is probably derived from *na-ulu* which would mean "the rolling ones."

the elevation of maximum rainfall is one indication of the difference in air flow. Apparently a 10,000-ft mountain forces the trade winds to flow around it, while a 5000-ft mountain, whose summit lies below the inversion, experiences predominantly over-top flow.

The trade wind flowing around the north side of Haleakala cone is lifted sufficiently to form an orographic cloud which persists nearly constantly. The cloud maintains a constantly dissipating edge parallel to a radial line perpendicular to the trade wind. At the surface the northeast trade wind passing over the isthmus is separated by a narrow shearline from a south-southeast flow. A map of surface wind directions for a sample day is presented in fig. 6. Surmounting this shearline is a long narrow cloud line which merges as the tail of the letter "J" with a bank of clouds lying north–south against the side of the Haleakala cone. The typical configuration of this cloud is also indicated on fig. 6.

It is clear by inspection of the surface wind directions that the cloud hugging the west face of Haleakala is caused by the orographic lifting of air flowing upslope from the southwest. This flow from the southwest is maintained only during the day, and on the west slopes of the mountain is replaced at night by a downslope wind, accompanied by dissipation of the daytime cloud bank. Non-instrumental observations indicate that the southwesterly flow of midday backs during late afternoon to the easterly downslope wind of evening. These characteristics establish the leeward wind regime as a sea–land breeze. Its position is such that it assists or partakes in whatever eddy motion is set up on the lee side of the cone by the flow of the trade wind, as will be discussed shortly.

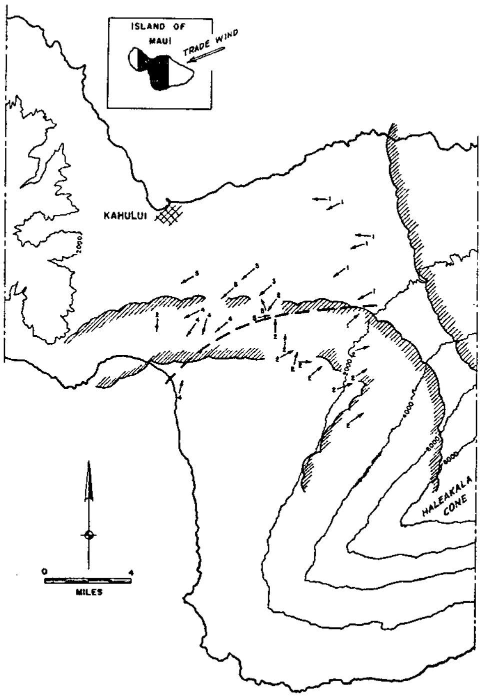

Fig. 6. Surface wind directions (arrows) over the central portion of Maui, 24 November 1948, showing the zone of interaction (dashed line) between the trade wind and the sea breeze. The numbers by the wind arrows give the observation time in hours past 1200. The outlines at 1300 of the sea-breeze (lower) and orographic (upper right) cloud masses are indicated by hatched lines.

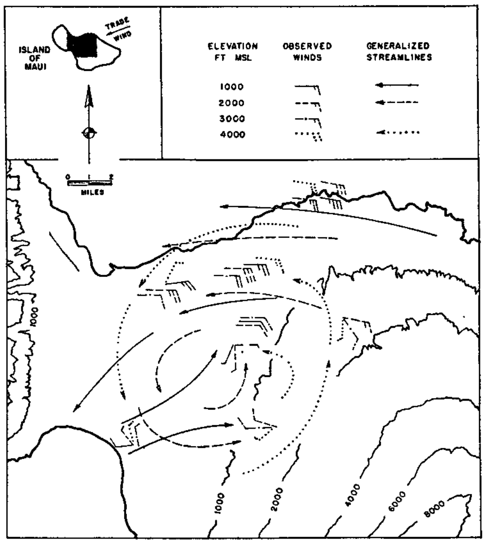

Fig. 7. Streamlines over central Maui at 1000-, 2000-, and 4000-ft levels based on pilot-balloon observations at 1200 local time. Composite map utilizing observations on 8, 9, 12, and 13 July 1948.

On the isthmus of Maui the trade wind and sea breeze blow nearly parallel to their zone of contact rather than perpendicular to it as on Lanai. The trade wind immediately adjacent to the shearline is often strong, 20–35 mi hr^{-1}. In a space of 100 yards it gives way to light southwesterly wind.

Because of the angle at which the winds meet, the shearline on the isthmus is not usually a zone of strong vertical currents. As one follows the shearline up the slope of Haleakala, however, the sea breeze has backed to a more southerly direction and this increased component of wind perpendicular to the zone of interaction provides a source of vertical motion. The sea-breeze cloud extending WSW over the isthmus consists, as in the case of Lanai, of clouds formed in the region of vertical motion and blown WSW under the influence of the trade winds aloft. The far southwest end of the sea-breeze cloud is continually dissipating and is constantly being replaced by those formed in the "cloud factory" close to the surface of Haleakala.

Generalized streamlines at the 1000-, 2000-, and 4000-ft levels above central Maui are shown on fig. 7, which was constructed from 32 pilot-balloon flights observed from the seven locations shown on the map. Fig. 7 indicates that the shear zone at the surface is gradually replaced at increasing elevations by a counterclockwise circular or eddy motion. Above this eddy motion the easterly trade winds were observed over the area at an elevation of 5–6000 ft and above.

(Of course, the trades are surmounted at still higher levels by westerlies.) These streamlines explain the observed motions of the cloud line. The zone of convergence in the 2000-ft winds particularly is indicated by the wind data.

A Maui sea-breeze cloud similar to the one described also exists on many days over the ocean on the south-southwest sector of Haleakala, when the trade wind is flowing around the southern side of the cone. It occurs over an area not readily accessible but appears to have the same characteristics as the one over the isthmus. On days when the subsidence temperature inversion is weak or absent, the sea-breeze cloud attains considerable vertical development and the rainstorms from this cloud are called naulus, just as on Molokai and Lanai. The area which, according to local residents, receives such rain most frequently, coincides exactly with the area under the sea-breeze cloud described in the present study.

The central Maui circulation consists, in brief, of a split trade-wind current with a sea breeze which blows upslope in the lee zone. The sea breeze dominates near the surface and interacts with the trade wind in a shear zone. In the levels from 2–5000 ft the shear is replaced by a counterclockwise eddy motion. At night a downslope land wind obliterates the tendency of the near-surface trade-wind streamline to eddy in the lee of the mountain.

4. The Mauna Kea type land-wind front

Mauna Kea (14,000 ft) on the island of Hawaii is the highest of the volcanic cones in the Territory. It is essentially conical but intergrades with the Mauna Loa cone (13,600 ft) in a saddle, the elevation of which is 6000 ft. In the vicinity of Umikoa (fig. 8) on the northeast flank of Mauna Kea, a downslope land breeze prevails at night. During the day an upslope wind is typical consisting of the trade-wind flow aided by a sea breeze. This situation has been briefly described previously by the writer (Leopold, 1948) but additional details may be added here. As was observed on the lee side of Haleakala, during the night the slope near Umikoa is clear due to the adiabatic heating in the land breeze. A bank of clouds stands offshore during the night, apparently over the zone where the land breeze meets the trade wind. Because the cloud bank is over the ocean, details of wind structure are not easy to obtain, but reasoning from the Lanai situation indicates the analogy. During the day the sea breeze-trade wind rising up the slope provides a deck of clouds against the mountain which usually persists from midmorning until dark. This offshore cloud bank is a "land-wind front" comparable to the "sea-breeze front" of Lanai. A similar phenomenon was observed in Puerto Rico by C. E. Palmer (unpublished note) who independently arrived at a similar explanation. In that case the cloud line was typically a line of thunderstorms.

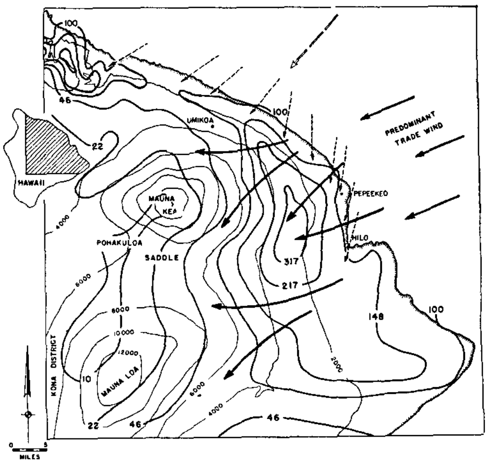

FIG. 8. Streamlines and mean annual rainfall on NE portion of Hawaii. Isohyetal lines (heavy isopleths) are in inches, logarithmic spacing. Short dotted arrows are observed directions of movement of cloud bases (at approximately 2500 ft msl) 3 April 1949; large dashed arrow is direction of trade wind at gradient level on same day. Heavy arrows are hypothetical mean streamlines.

The clear skies at night in the Umikoa area and the daytime cloud bank caused by the upslope trade wind sea breeze gives that locality a daytime rainfall maximum. Proceeding southward, however, this is replaced by a nocturnal rainfall maximum in the Hilo-Pepeekeo area, typical of all windward and crest areas where normal trade wind orographic rainfall is dominant. It is interesting to conjecture how the land breeze can be sufficiently strong to counteract the trade wind at night. The explanation does not lie in a decrease of trade wind at night, a characteristic of the trade near sea level. As indicated previously (Leopold, 1948) Honolulu pibals show that at 2000 ft msl. the mean speed of the trade wind is greater at night than during the day.

The splitting of the trade current by Mauna Kea would furnish an explanation. This splitting would no doubt tend to provide a decreased component acting against the mountain at least in the area of horizontal divergence where the trade is splitting. This local weakening of the onshore component would thus allow the nighttime land breeze to dominate.

If the trade wind were forced to rise directly over the mountain peaks with no tendency to split and flow around, one would expect to find two zones of maximum rainfall on Hawaii, located on the exposed flanks of Mauna Loa and Mauna Kea respectively. Actually there is a single area of maximum rainfall as can be seen on fig. 8. The isohyetal maximum is located about midway between two lines parallel to the trade wind and drawn through the apexes of the two cones. As in the case of Haleakala, the maximum rainfall occurs at an elevation of 3–4000 ft, decreasing at higher elevations.

The splitting of the trade wind under the inversion is indicated by observed directions of the cloud bases. A series of nearly simultaneous observations of cloud bases at various points around the base of the Mauna Kea cone are shown as dotted arrows on fig. 8. No such split flow can be observed around the lower mountains of other islands. Streamlines drawn in accordance with the observed splitting of the trades by each of the two cones, Mauna Loa and Mauna Kea, would converge directly over the observed zone of greatest rainfall. This convergence is undoubtedly the explanation for the position of the isohyetal maximum and the notorious wetness of the Hilo-Pepeekeo locale. The Kohala Mountains to the north (maximum elevation 5500 ft) apparently are not high enough to split the trade wind into two currents, and the maximum rainfall occurs near the summit.

As mentioned previously, it is presumed that the temperature inversion lying well below the top of the higher mountains is an important factor in forcing the air to flow around rather than over the mountain. Long experience observing orographic clouds in Hawaii establishes the fact that the cloud tops, which are uniformly at the level of the inversion base over the ocean, rise very little over the mountain peaks. Where the peaks extend above the inversion practically no upward slope of cloud tops is observable where they lie against the mountain. Measurements of cloud top profiles over the mountains have recently been made by Mordy[3] who found that cloud tops over the 3000 ft Koolau Range on Oahu are lifted about 300 ft above the uniform cloud top level of the surrounding ocean.

It appears probable, then, that the inversion base is lifted only very small amounts by air flow over or around the mountains.

5. The Kona sea breeze

In the lee of Mauna Loa is a large area more or less protected from the trade winds. This district, known as Kona, experiences a sea breeze during the day and a land wind at night. Convective clouds form over the land or near shore and blow inland during the day where they provide the source of frequent summer showers. On summer afternoons the area usually becomes overcast with such clouds. This characteristic results in a larger summer rainfall than that of many otherwise similarly situated areas, and provides a summer rainfall maximum in contrast to the winter maximum of the bulk of the Territory.

These convective rainshowers blowing upslope in the sea breeze are more frequent and more important in Kona than elsewhere because of the large size of the area protected from the trades. Yet except for these characteristics attributable to its size, the Kona area is comparable to the lee slopes of Haleakala. At the southern extremity of Kona, a sea-breeze cloud extending far out to sea in a westerly direction is common, and can be seen clearly from Kalae (South Point) or from Kahuku Ranch. The interaction of the trade wind and sea breeze which produces this cloud line must be similar to that over the isthmus of Maui; the interaction is probably a shearline parallel to which the two wind systems blow, but in opposite directions, with the main cloudforming convergence concentrated adjacent to the mountain mass.

At the north end of the Kona area a daytime sea breeze blows inland as far as the crest of the saddle which separates Mauna Loa and Mauna Kea. At Pohakuloa, on the saddle crest (fig. 8), the sea breeze from the west and the easterly trade wind meet and set up a small sea-breeze front similar to that of Lanai. Clouds blowing toward the saddle in the trade wind generally dissipate at the saddle crest before reaching the sea breeze. These clouds (which touch the ground surface and might be called fog) are singularly free of turbulent motion, presumably due to the lifting which has increased stability. At the point of dissipation, these clouds often disperse in the form of rain. This dissolution of clouds into raindrops is an example of the colloidal instability frequently observed in Hawaii.

The trade-wind air moves westward over the saddle, and within a mile of the point where the orographic cloud has dissipated, rises over the sea breeze which is blowing toward the saddle from the west. Clouds in the sea-breeze flow are blown toward the zone of interaction, and when they reach the trade wind flowing up over the sea-breeze tongue, the cloud tops are caught in the trade wind and a strong turbulent motion is observed.

6. Summary of interaction types

We have discussed four more or less different types of interaction of sea breeze and trade wind. The interactions depend primarily on three factors: (*1*) the breadth of the area on which heating and cooling will occur to cause the land and sea breezes, and which presumably governs the strength of the breezes so developed; (*2*) the height and shape of the mountain range which, in relation to the subsidence temperature inversion, will determine whether the trade wind will rise over the top or tend to split into two currents, passing one on either side; (*3*) the aspect of the area on which the sea–land wind regime develops (exposure windward or leeward with respect to the trade wind).

It is clear that the four types of interactions grade one into another as the three determining factors are

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[3] W. A. Mordy, "Vertical cross sections through orographic clouds in Hawaii," 1949 (unpublished).

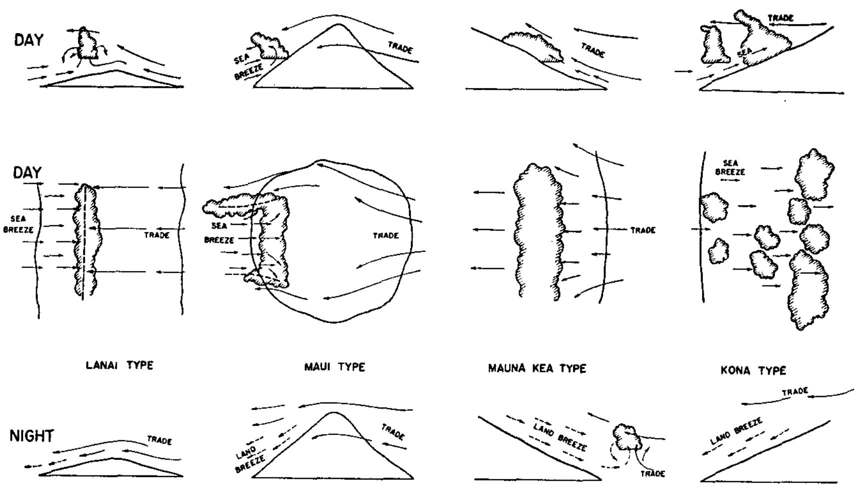

FIG. 9. Schematic representation of four types of interaction of sea breeze and trade wind. Daytime conditions (top and middle) shown in vertical and horizontal sections with nocturnal conditions (bottom) shown in vertical section only.

progressively altered. The four examples represented in fig. 9 can, in a general way, be used to classify all the types of interactions seen in the Territory of Hawaii and probably would apply to many other insular locations where a prevailing general wind interacts with local winds. In fig. 9 it can be seen that the Lanai type represents islands too low to split the trade into two prongs, but rather allows the trade wind to flow over the ridge. The trade meets the sea breeze in a line perpendicular to the trade direction. In this type the trade might meet the sea breeze at the crest line of the ridge as it does over west Molokai, or to the lee of the crest as on Lanai. In modified form it represents the Honolulu area in which the lee coastal plain is so narrow that a sea breeze component equals or exceeds the trade wind flow only infrequently.

Fig. 9 shows the Maui type as representing a mountain large enough to split the trades, but not having a lee area of sufficient size to develop important convective showers unrelated to the interaction of sea breeze and trade wind. The zones of interaction are shearlines not productive of much vertical motion except near the mountain slope. The northwest corner of Kauai appears to exhibit Maui type circulation. The Upolu region of the island of Hawaii (northwest tip) is a combination of the Maui and Lanai types. The Kona type is a large lee area over which ordinary convective clouds produce important amounts of rain. The tops of the clouds may at times extend high enough to reach the trade flow but the clouds generally blow inland on a deep sea-breeze current. Maui type zones of interaction might characterize the edges of the Kona type.

In those types related to the lee side of a mountain, the nighttime land wind reinforces the trade-wind flow and provides more or less clear skies at night. In the windward side Mauna Kea type, it is the sea breeze which reinforces the trade, but the land breeze is stronger than the diverging trade flow and thus provides clear skies at night. Where there is no splitting of the trade or where the divergent area is not wide, the land wind is not sufficiently strong to reverse the trade wind, and under such circumstances there is no clearing of windward slopes at night.

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