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This study of the mountain cloud and fog regimes on the windward and leeward slopes of Mauna Loa, Hawai'i Island (1) develops a standardized louvered-screen, fog-catchment gage; (2) develops an indirect approximation method for estimating average droplet sizes during precipitation episodes and for separating the rainfall and fog components; (3) establishes an extensive fog sampling network on the windward and leeward slopes of Mauna Loa; and (4) develops an original computer program for detailed temporal and spatial analyses of rainfall, fog, and wind parameters.

An analysis of data for the 1974 to 1976 period yielded the following conclusions: (1) a well-defined fog belt exists on windward Mauna Loa in the altitudinal zone between 1 500 to 2 500 m with fog-catchment amounts as great as one-half the rainfall, or about 750 mm; (2) mountain fog on leeward Mauna Loa increases with elevation up to at least 2 000 m, with fog amounts equivalent to one-fourth the rainfall, or about 250 mm; (3) seasonal and altitudinal patterns in fog frequency and catchment amounts are related to the dynamic interaction of the tradewind field (particularly the tradewind inversion) and the local land/sea breeze regime; (4) mountain fog appears to be a significant factor in the water balance of mountain ecosystems on Mauna Loa; and (5) the potential for large-scale mechanical recovery of fog water may exist for selected locations on Mauna Loa.

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A CLIMATOLOGY OF MOUNTAIN FOG ON MAUNA LOA
HAWAI'I ISLAND

by

James O. Juvik
Paul C. Ekern

Technical Report No. 118

June 1978

Project Completion Report
for

Fog Precipitation Along Topo-Climatic Gradients
on the Island of Hawai'i

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ABSTRACT

This study of the mountain cloud and fog regimes on the windward and leeward slopes of Mauna Loa, Hawai'i Island (1) develops a standardized louvered-screen, fog-catchment gage; (2) develops an indirect approximation method for estimating average droplet sizes during precipitation episodes and for separating the rainfall and fog components; (3) establishes an extensive fog sampling network on the windward and leeward slopes of Mauna Loa; and (4) develops an original computer program for detailed temporal and spatial analyses of rainfall, fog, and wind parameters.

An analysis of data for the 1974 to 1976 period yielded the following conclusions: (1) a well-defined fog belt exists on windward Mauna Loa in the altitudinal zone between 1 500 to 2 500 with fog catchment amounts as great as one-half the rainfall, or about 750 mm; (2) mountain fog on leeward Mauna Loa increases with elevation up to at least 2 000 m, with fog amounts equivalent to one-fourth the rainfall, or about 250 mm; (3) seasonal and altitudinal patterns in fog frequency and catchment amounts are related to the dynamic interaction of the tradewind field (particularly the tradewind inversion), the local land/sea breeze regime, and rainfall; (4) mountain fog appears to be a significant factor in the water balance of mountain ecosystems on Mauna Loa; and (5) the potential for large-scale mechanical recovery of fog water may exist for selected locations on Mauna Loa.

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INTRODUCTION

In virtually every year over the past decade one or more districts on Hawai'i Island have been declared a "drought disaster area" by the county government, resulting in the imposition of mandatory water restrictions and government-subsidized hauling of domestic water. The frequency of drought in Hawai'i is directly related to the very high annual and seasonal variability in rainfall that characterizes most areas of the island.

The cattle industry on Hawai'i Island is particularly susceptible to the vagaries of rainfall. Most grazing operations are concentrated at 1 000- to 2 000-m elevations, generally above the high rainfall belts. Since it is not economical to pump well water to these elevations, ranches are almost completely dependent on surface water catchment to supply agricultural needs. The type and size of surface catchments vary with individual ranch requirements.

Due to the high rainfall variability and to the consistently low summer rainfall in most mountain areas of the island, the excessive capital investment costs required to assure protection from periodic drought (as provided by expanded catchment and storage capacity) cannot be justified. To compound this problem, water catchment systems are frequently located at the highest elevation possible, in spite of the fact that annual rainfall above the tradewind inversion decreases with elevation, so that the water distribution system can operate by gravity feed. The lower collection efficiency of catchments installed at high elevation is offset by the pumping costs that would otherwise be incurred to bring water uphill, were the catchment located lower on the slope.

Mountain fog occurs frequently in association with orographic or convective precipitation on Mauna Loa and Mauna Kea but can also occur in the absence of rainfall. This is particularly true during the summer months when increased atmospheric stability limits vertical development of the orographic cloud.

This fog is important as a potential water source because mountain upslope fog is one of the few kinds of fog that can persist with relatively high wind velocities. This results in extremely large volumes of water passing near the ground. As an example, if a mountain fog contains only a modest 0.5 g/m^3 of water and wind maintains a velocity of 4 m/s, 2.12 x

10^{-6} m^3/s of water pass through a vertical area of 1 m^2.

If this fog water might be economically extracted by a vertical catchment system, it could represent an important augmentation of the water supply to island ranchers. The relative economy of a large-scale fog catchment system in a specific area would depend on a cost/benefit analysis of the comparative expense and efficiency of vertical fog collectors versus more traditional surface rain catchments. Such an analysis would necessarily incorporate consideration of seasonal distribution and intensities of the respective precipitation types as well as absolute annual totals.

A yet larger set of questions relates to the role of fog catchment by trees in maintaining natural ecosystems and in the hydrologic balance of the island. During the past two centuries man has caused serious destruction of the mountain forests on Hawai'i (Mueller-Dombois and Krajina 1968). The subalpine māmane (*Sophora chrysophylla*) and naio (*Myoporum sandwicense*) forests have been drastically reduced in areas on both Mauna Loa and Mauna Kea, primarily as a result of uncontrolled browsing by introduced feral animals (Warner 1960). The subjacent koa (*Acacia koa*) forest zone has likewise been largely eliminated through the combined effects of commercial logging, clearing for pasture, and browsing by feral and domestic animals (Spatz and Mueller-Dombois 1972). Even the extensive 'ōhi'a (*Metrosideros* spp.) on the lower slopes have not escaped widespread devastation. "'Ōhi'a-dieback," the cause of which is as yet indeterminate, has reached epidemic proportions on Hawai'i, laying waste tens of thousands of hectares of forest watershed.

The implications of this collective forest destruction for the island water supply are at present poorly understood. Very high infiltration rates and the rapid revegetation of many areas by herbaceous plants have reduced the serious erosional consequences normally associated with widescale deforestation. While actual mountain rainfall is likely to be little affected by forest clearing, the effect of forest removal with respect to fog interception may be significant. To the extent that ground-level mist and fog interception are diminished by forest destruction, this moisture is totally lost to the island, i.e., advected to leeward.

In an early analysis of the weather of Mauna Loa and Mauna Kea, Powers and Wentworth (1941) commented on the frequency of ground-level mist and fog and the abundant fog drip from māmane trees (at the 2 000-m level). They were also impressed by the rapidity with which the rising orographic cloud dissipated by evaporation to the lee of the mountains.

Any general assessment of the true quantities of moisture involved would require detailed knowledge of both the spatial distribution, frequency, and intensity of mountain fog, as well as the interception catchment efficiencies of forest types that occupy, or once occupied, the mountain slopes (Merriam 1973).

RESEARCH OBJECTIVES AND SCOPE

The primary goal of this study is the development of a quantitative, spatial characterization of the mountain fog regime on Mauna Loa that could serve as a data base for evaluating the role of fog in the forest hydrology of that mountain and the potential economic feasibility of large-scale, mechanical fog water recovery for domestic and agricultural water supply on Hawai'i Island.

The basic goal is approached through the following specific research objectives:

1. The development of a mechanical fog-interception gage and the formulation of a measurement methodology capable of isolating the fog component of precipitation episodes and relating mechanical interception data to actual forest interception
2. A quantitative description of the spatial patterns of annual and seasonal fog frequency and intensity on Mauna Loa
3. The development of a "general slope model" for mountain fog on windward and leeward Mauna Loa through the analysis of empirical relationships between mountain fog and associated topo-climatic variables, e.g., rainfall, elevation, and slope.

There are two basic approaches to the measurement of mountain fog: actual fog drip may be collected from beneath forest canopies, or the fog itself may be directly intercepted from the air by mechanical means. The advantages of either approach depend on the objectives of the fog-monitoring program. The measurement of undercanopy fog drip can provide precise data on the contribution of fog to forest water balance at a specific site. However, because of normal canopy heterogeneity, "...excessively large numbers of collectors are required to obtain reasonably accurate and precise data, and this problem becomes particularly bothersome in comparative studies..." (Kimmins 1973, p. 1017). Because of the wide variation in

vegetation types on Mauna Loa and the substantial physiognomic variation that may even occur within a given forest type, the direct measurement of fog drip is not feasible for large-scale spatial analysis of mountain fog.

Mechanical interceptors offer an advantage in comparative studies by providing standardized measurements with a minimum of sampling stations. For specific areas where forest fog-drip data may be required, the mechanical fog interceptor can be calibrated with short-term canopy throughfall measurements. One problem frequently encountered in the use of mechanical fog interceptors is the interpretation of gage output when rainfall and fog occur together in the same precipitation episode. The present study offers a solution to this problem.

With few exceptions, previous quantitative studies of mountain fog have been restricted to ridge and summit sites where increased wind speeds and the funneling of clouds may lead to impressive amounts of fog interception and drip. Summits and ridges, however, make up only a small fraction of the land area in mountains, and, thus, fog catchment at such unique sites plays a lesser part in comparison to the fog catchment on the more extensive slopes of the entire watershed.

In the present study, emphasis is placed on the measurement and modeling of "general slope" fog conditions, which are of much greater ecosystem significance.

The study area for this research on Hawai'i Island was restricted to Mauna Loa, as opposed to Mauna Kea, primarily because (1) Mauna Loa exhibits a more pronounced differentiation of climates on its windward and leeward aspects; (2) the existing climatological data base, e.g., rain-gage stations, is better developed for Mauna Loa; and (3) there are more drought affected surface water users on Mauna Loa who might potentially benefit from the application of fog-water recovery technology.

METHODOLOGY

Louvered-Screen Fog Gage

In the present study a standardized fog gage (Ekern 1964) was developed utilizing a louvered-screen cylinder (kaiser Shadescreen) mounted within a stainless steel drainage funnel. A flexible plastic hose drained the fog-gage funnel into a (covered) standard 20.3-cm (8-in.) rain gage. The louvered-screen fog gages were mounted upon tubular steel tripods with the

center of the louvered-screen interceptor set at 3 m above the ground. The specific size dimensions of the louvered-screen gage are provided in Figure 1. A screen cylinder, 12.7 cm in diameter and 41.9 cm in height (1 672 cm^2 surface area), was mounted within a larger drainage funnel (15.2-cm diam).

A fog gage of this design collects rainfall as well as fog. The fog component may be derived from the difference between the louvered-screen gage output and that of a companion standard rain gage. The cross-sectional area of the fog-gage drainage funnel (15.2-cm diam) is 179.5 cm^2 or 56% of the 324.3-cm^2 area of a standard 20.3-cm rain gage. Therefore, if 56% of the rain-gage value is subtracted from the fog-gage output, any excess should be attributable to fog and rainfall intercepted on the screen. The screen surface area of 1 672 cm^2 is 5.0 times the cross-sectional area of the standard rain gage.

Since a tree often has a vertical silhouette (Ekern 1964) just equal to the horizontal area it occupies, the actual fog-gage catchment is converted to that for vertical area just equal to the area of the rain gage, hence the *unit vertical catchment* is 1/5 the actual fog catchment, as $F = (f - 0.56R)/5.0$ where f is the fog catchment depth in a standard gage, R is the rainfall. In the following discussion of mountain fog on Mauna Loa, unless otherwise specified, all fog values are expressed in terms of unit vertical catch.

Nonvertical Rainfall and the Louvered-Screen Fog Gage

As explained in the preceding section, the louvered-screen fog gage collects rainfall as well as fog. However, simple subtraction of the rainfall component, as measured in a companion rain gage, may not necessarily yield a true picture of fog interception if nonvertical rainfall has also occurred during the sampling period. Grunow (1952) found that, in the absence of fog, a rain gage equipped with a fog catcher collected about the same total amount of rainfall as a standard rain gage over a period of a year, although for individual precipitation episodes there often were substantial differences between the gages. Nagel (1956) considered these individual episode discrepancies to be a function of variations in wind speed and droplet size. In the case of very light rainfall, some of the rain would adhere to the fog screen and evaporate, leading to potentially higher readings in the standard rain gage. By contrast, when large rain

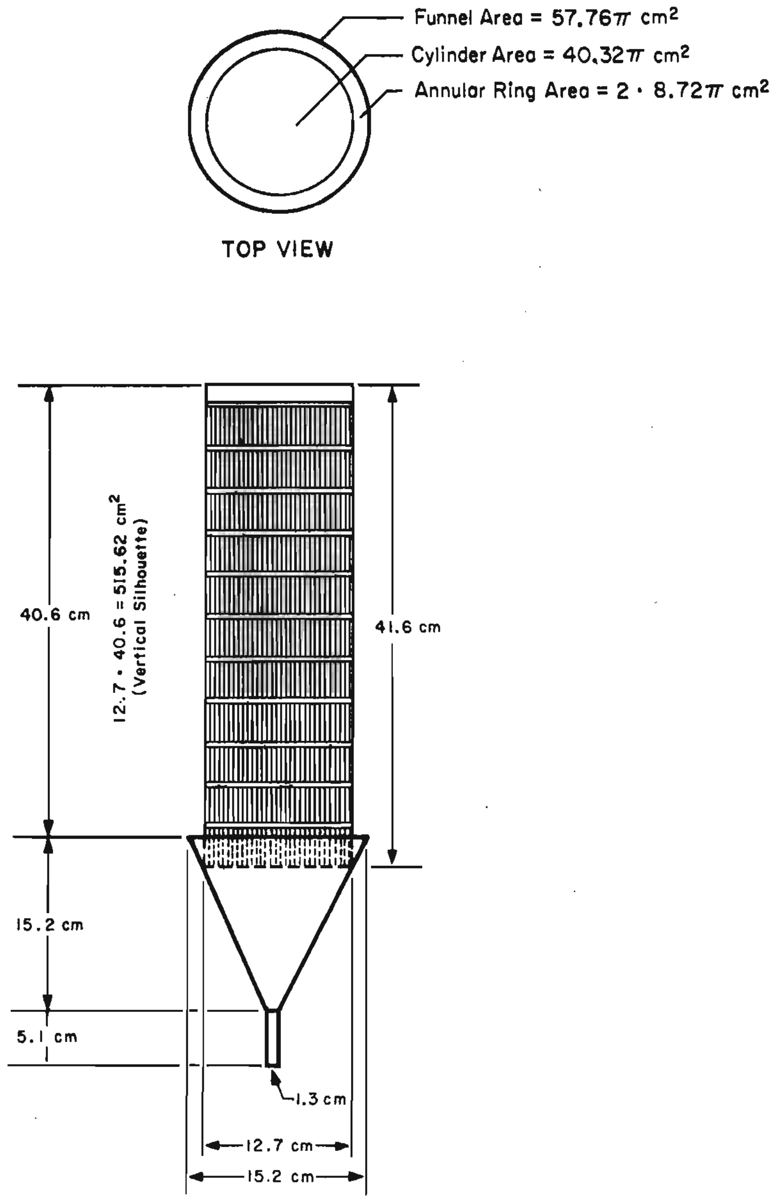


FIGURE 1. LOUVERED-SCREEN FOG GAGE SCHEMATIC

droplets fall in moderate to strong wind, the increased vertical silhouette of the fog gage (relative to the cross-sectional area of the rain gage) would result in a collection bias favoring the fog gage.

The results from a louvered-screen fog gage and companion standard rain gage at 610 m on windward values (Waiākea Station) in an area of relatively heavy rainfall with no ground fog illustrate the possible influence of nonvertical rainfall on the fog gage. The relationship for 28 weeks in 1972 shows almost identical values for each gage (Fig. 2). At lower precipitation values there is a small bias in favor of the rain gage, consistent with the earlier observation that evaporation from the fog-gage screen may slightly diminish fog-gage output at low rain intensities. The bias shifts to slightly favor the fog gage at higher intensities, a result again consistent with Nagel (1956).

The calibration results presented in Figure 2 are clearly consistent with the conclusions of Grunow (1952) that, over the long term, discrepancies between the two gages with respect to rain collection are inconsequential, and that increased output from the screen cylinder can be attributed to fog interception rather than nonvertical rain. However, for the indvidual

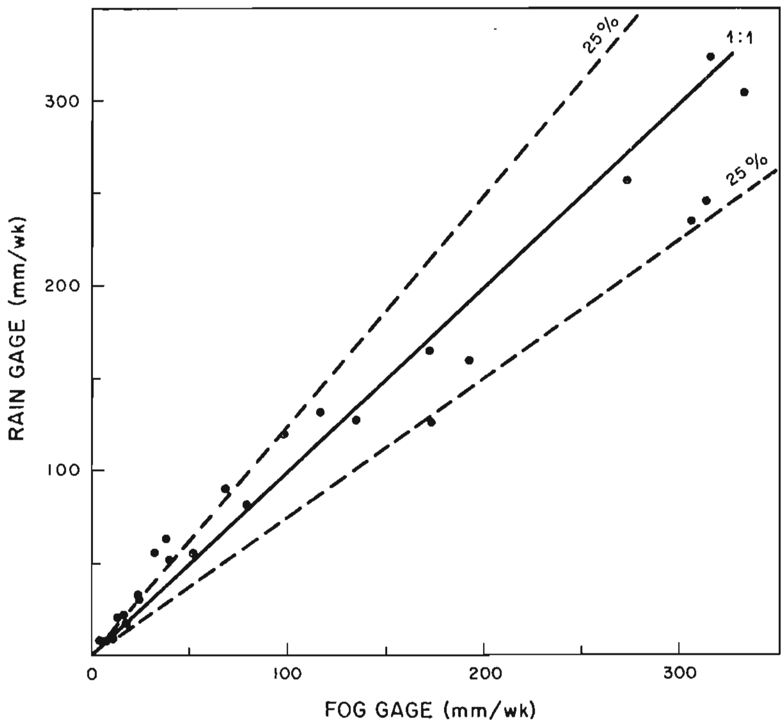


FIGURE 2. RELATIONSHIP BETWEEN WEEKLY RAIN- AND FOG-GAGE OUTPUTS FOR RAIN-ONLY (FOG ABSENT) EPISODES, WAIĀKEA STATION (610-m el.), WINDWARD MAUNA LOA, HAWAI'I ISLAND, 1972

precipitation episode, the substantial deviations evident in Figure 2 indicate the difficulty of clearly separating the fog and nonvertical rainfall components for hourly or daily analysis. Interpretation based on the differences in catch between a fog gage and a rain gage depends on a measure representative of the "true" precipitation. This measurement is beset by many hazards, such as differences in gage diameter, elevation, orientation, and wind shielding (Larson and Peck 1971; Sevruk 1974). The rainfall catch for the fog gage at the 3-m elevation is less than that for a standard surface gage; but the actual difference is unknown, and no account is made of this difference in the analyses in this report.

For individual precipitation episodes, if mean droplet sizes or the average inclination angle of arriving droplets were known, it would be possible to determine with more certainty whether differences between the fog-gage output and rain gage could be attributed to fog or simply large raindrops arriving on an inclined path, due to strong wind (Hudson 1964). In the present study, no instruments were available to continuously monitor and record droplet sizes or inclination angles. It was, however, possible to estimate the average inclination angle of arriving droplets on the basis of fog- and rain-gage geometries. As has been shown in Figure 1, the relationship between the fog-gage silhouette area and the cross-sectional area of the standard rain gage changes as a function of the inclination angle of the arriving rain and fog drops. The effective area for rainfall catchment when drops fall at an angle, α, from the vertical with a standard rain gage is $\cos \alpha \; 10.16^2\pi = \cos \alpha \; 103.23\pi \text{ cm}^2$. The area for rainfall collection by the fog gage includes the vertical silhouette of the screen cylinder as well as the area of the funnel. The area of the screen is $12.7 \cdot 40.6 \text{ cm}^2$ and the effective catchment area for raindrops falling at angle, α, is $515.62 \cdot \sin \alpha$. The entire horizontal area enclosed within the screen cylinder is open to rainfall and the effective catchment area is $\cos \alpha \cdot 6.35\pi^2$. If rainfall is inclined more than 2 degrees from the vertical, the additional area of the annular ring between the cylinder wall and the rim of the funnel in the lee of the axes of the screen cylinder is shielded and does not collect rainfall. The portion of the annular ring exposed to rainfall catchment is thus one-half the annular ring plus twice the half segment of the funnel and lee of the axis of the screen.

The complete area of the fog gage for catchment of raindrops falling

at angle, α, is thus,

$$\text{Area} = 515.6 \sin \alpha + (40.32\pi + 8.72\pi + 7.125)\cos \alpha$$

The ratio between the areas effective in catchment of raindrops falling at angle α for the fog gage and that for the rain gage becomes

$$\text{Ratio} = \frac{515.62 \sin \alpha + (49.04\pi + 7.125)\cos \alpha}{103.23 \quad \cos \alpha}$$

It will be noted from Figure 3 that at an inclination angle of 0°, vertical rainfall, the fog gage will have a catchment area 56% of the rain gage. At a precipitation angle of 45°, the fog gage would present a silhouette catchment area about twice the rain-gage catchment area. From this ratio, the angle of inclination of the raindrops, α, can be derived as:

$$\text{ratio} = \frac{515.62 \tan \alpha}{103.23\pi} + \frac{49.04\pi}{103.23\pi} + \frac{7.125}{103.23\pi}$$

$$= \frac{515.62}{324.31} \tan \alpha + 0.475 + 0.022$$

$$= 1.59 \tan \alpha + 0.497$$

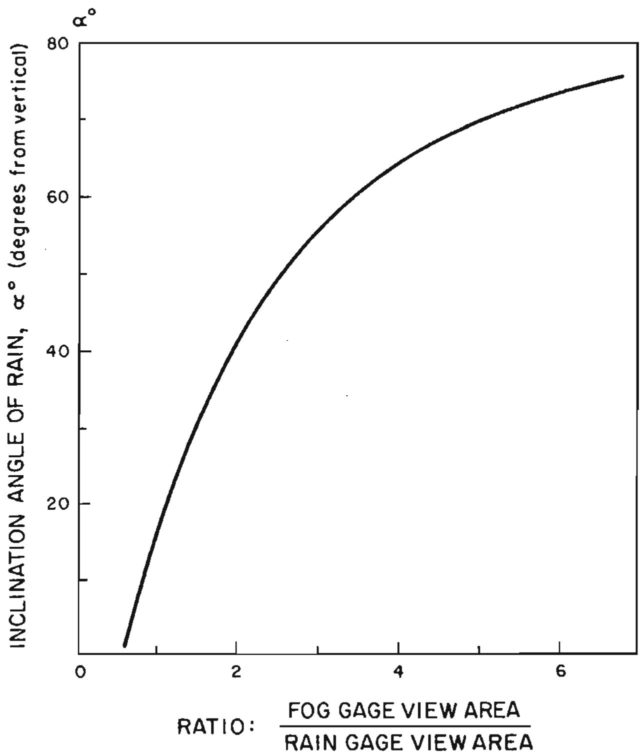


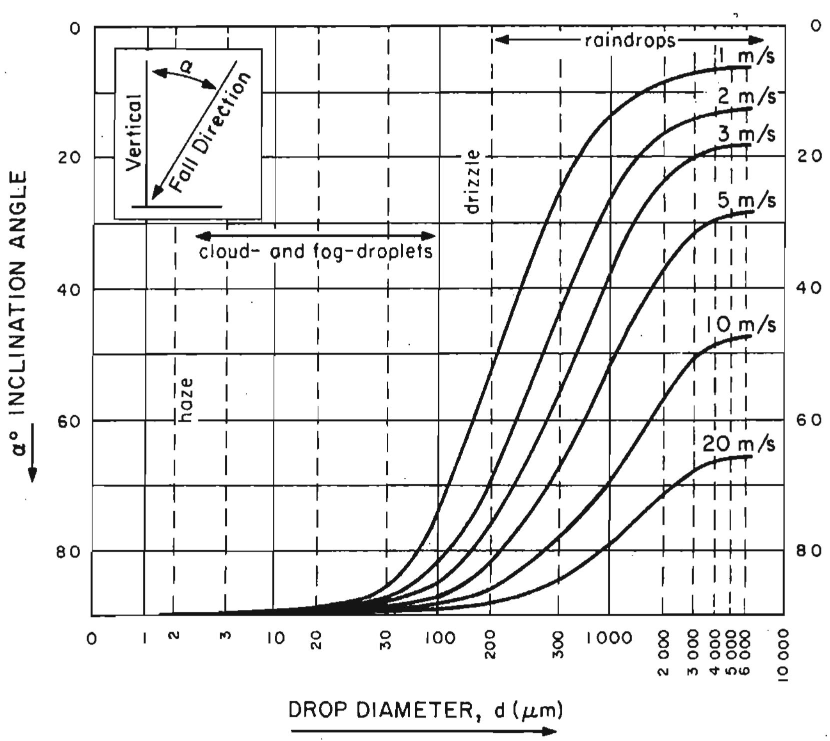
FIGURE 3. RELATIONSHIP BETWEEN THE FOG- AND RAIN-GAGE CATCHMENT AREAS AS A FUNCTION OF PRECIPITATION INCLINATION ANGLE

$$\tan \alpha = 0.629 \text{ ratio} - 0.313$$

$$\alpha = \tan^{-1} 0.629 \text{ ratio} - 0.313$$

Thus, the ratio of fog-gage to rain-gage output can be used to calculate the mean inclination angle, α, of arriving droplets.

Nagel (1956) has calculated the physical relationship between inclination angle, droplet size, and wind speed (based on the terminal velocity of fall for water droplets determined by Gunn and Kinzer [1949]). Figure 4 shows the angle (from vertical), at which droplets of different size fall in a horizontal, laminar air stream at different air speeds. On the basis of this graph, it is possible to calculate the mean droplet size if the inclination angle and wind speed are known.



SOURCE: Nagel (1956).

FIGURE 4. RELATIONSHIP BETWEEN DROP DIAMETER, INCLINATION ANGLE, AND WIND VELOCITY

With the wind speed, employing the relationships presented in Figures 3 and 4, it is possible to estimate an approximate droplet size for the individual precipitation episodes (for further elaboration see McKnight and Juvik [1975]). In order to test the validity of this drop-size estimation procedure, simultaneous direct droplet size measurements, utilizing the magnesium oxide method (May 1950), were taken during 16 individual precipitation episodes at the Hawaii Volcanoes National Park. While the magnesium oxide method provides accurate quantitative measurement only for drops in the range from 10 to 200 µm, larger droplets (500-1 000 µm and above) are easily distinguished and assigned to broad size categories, e.g., between 500 to 1 000 µm, or >1 000 µm.

The mean droplet diameters are based on $N \geq 100$ drop measurements for 16 episodes of 0.25- to 40.75- hr rainfall duration. It will be noted in Table 1 that the estimated mean droplet diameters show close and consistent correspondence to the measured values. With reference to episodes 11 to 16, where water is recorded only in the fog gage, the measured drop-size values confirm that this precipitation is indeed fog, rather than nonvertical rain.

On the basis of these results, an original computer program was developed, incorporating the relationships presented in Figures 3 and 4, to analyze rain, fog, and wind data for individual precipitation episodes (McKnight and Juvik 1975). This computer program is used to segregate rain and fog episodes on the basis of average droplet sizes. Once isolated, rain and fog periods can then be compared with respect to temporal occurrence, directional origin, and synoptic conditions.

Fog Sampling Network

Site selection criteria for the installation of a fog-gage network on Mauna Loa are based on a number of related sampling assumptions and constraints:

1. Mountain fog is primarily a mid-elevation phenomenon (Juvik and Perreira 1974) and, therefore, sampling was concentrated in the altitudinal zone between 1 500 and 2 500 m.
2. Within this general zone, sampling density was increased for the relatively drier, i.e., low rainfall, leeward areas where the potential contribution of fog in the water balance might be more significant in terms of the economic feasibility of large-scale

TABLE 1. MEASURED AND PREDICTED MEAN DROPLET SIZES FOR FOG AND RAINFALL EPISODES AT HAWAII VOLCANOES NATIONAL PARK (el. 1 200 m), HAWAI'I ISLAND

Episode	Date	Duration (hr)	Rainfall	Fog Catch	Wind Speed (m/s)	Drop Inclination Angle (°)	Terminal Velocity (m/s)	Est. Avg. Drop Diam (µm)	Measured Avg. Drop Diam (µm)
			------(mm)------						
1	11/26/73	1.25	1.8	1.5	1.57	11.4	77.7	2 307	>1 000
2	11/30/73	40.75	364.0	450.1	3.02	23.0	7.10	2 017	>1 000
3	12/01/73	37.75	539.0	835.1	3.82	31.4	6.27	1 696	>1 000
4	04/20/74	3.00	8.4	8.1	1.27	15.0	4.73	1 195	>1 000
5	04/08/74	4.00	1.8	3.0	2.53	35.3	3.58	876	>500
6	12/10/73	1.00	1.8	1.8	1.01	15.9	3.52	862	<1 000
7	12/09/73	1.00	1.8	3.0	1.96	35.3	2.77	673	<500
8	12/04/73	5.75	1.8	10.4	2.60	72.4	0.83	223	185
9	11/28/73	2.25	0.3	2.3	2.73	78.7	0.55	159	175
10	11/28/73	4.45	0.4	3.3	2.05	82.3	0.28	98	75
11	12/05/73	2.50	0.0	1.0	1.74	90.0	*	*	75
12	11/29/73	1.25	0.0	0.8	2.46	90.0	*	*	30
13	11/25/73	0.75	0.0	0.8	1.64	90.0	*	*	61
14	04/16/74	0.25	0.0	0.3	3.35	90.0	*	*	71
15	04/12/74	0.25	0.0	0.3	1.12	90.0	*	*	19
16	02/08/74	0.25	0.0	0.3	3.58	90.0	*	*	30

*No rainfall.

mechanical recovery of fog water for agricultural or domestic water supply.

3. Ideally, sampling should be undertaken with a series of adjacent parallel transects extending from low to high elevation on both the leeward and windward slopes. This sampling pattern would facilitate spatial analysis of both altitudinal and cross-slope variations in fog interception.
4. The selection of fog sampling sites should be limited to locations with existing rain-gage stations and long-term precipitation records. Because the fog study was programmed to extend for only one to three years, and due to the high seasonal and annual precipitation variability that is characteristic of the island, it is considered essential that fog sampling be restricted to sites with good rainfall records. This constraint would permit the short-term study results to be viewed, and interpreted, within the general context of precipitation normality during the sampling period.
5. Fog-gage sites should be limited to open, exposed locations with a clear "down-slope view." Because this study is primarily concerned with the spatial distribution of mountain fog, "typical" or representative slope sites are favored over ridge crests, promontories, or summit locations where the propensity for a typical fog enhancement is well documented and of little value in extrapolating general slope, i.e., watershed conditions.

With respect to the above sampling criteria, the requirement that fog monitoring be restricted to existing rain-gage stations severely limits potential fog sampling sites. There are only about 20 rain-gage stations within the 1 200-km^2 area of Mauna Loa lying above the 1 500-m contour (DOWALD 1973). In addition, these stations are not evenly dispersed but rather are bunched along the few jeep roads that penetrate the upper mountain zone. Since, in the present study, mountain access was similarly restricted to these few jeep roads, the fog sampling network is necessarily distorted from the ideally dispersed pattern outlined in item 3 above.

Within the limitations of mountain access and available rain-gage stations, a total of 18 fog sampling stations was established along five altitudinal transects on Mauna Loa and adjacent Hualālai. The distribution

of the sampling network is portrayed in Figure 5, with the site characteristics for individual stations presented in Table 2.

Transects A (windward) and C (leeward) constitute the primary sampling profile, and together provide good altitudinal coverage of both the windward and leeward slopes of Mauna Loa. To windward, Transect B located within the Hawaii Volcanoes National Park provides only a partial altitudinal overlap with Transect A. The lack of alternative mountain access on the windward side precluded establishing additional transects with altitudinal ranges comparable to Transect A. To leeward, Transects D and E offer good altitudinal overlap for the primary Transect C.

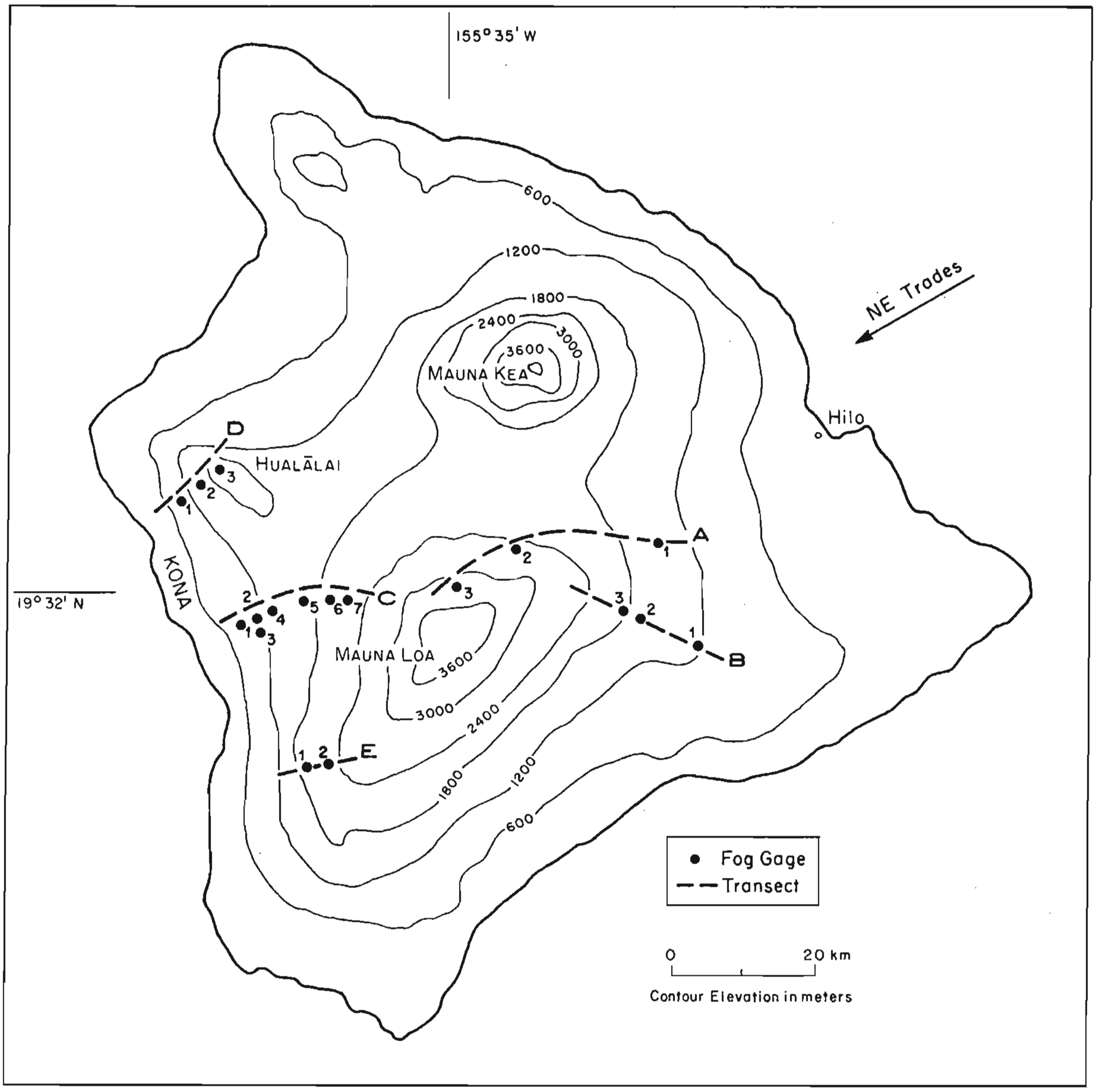


FIGURE 5. LOUVERED-SCREEN FOG GAGE SAMPLING NETWORK ON MAUNA LOA AND HUALĀLAI, HAWAI'I ISLAND

TABLE 2. FOG SAMPLING STATIONS ON MAUNA LOA, HAWAI'I, 1974-1975

Sta. No.	State Key No.	USWB No.	Station Name	El. (m)	Aspect	Monitoring Frequency	Months of Data	Surrounding Vegetation	Comments
A-1	79	5011	Kūlani Camp	1576	ENE	Daily	24	Closed 'ohi'a forest	Daily fog/cloud observations by prison personnel
A-2	76	5018	Kūlani Mauka	2530	NE	Weekly	24	Alpine shrubs	--------
A-3	39	6198	Mauna Loa Slope Obsv.	3397	N	Weekly	24	Barren lava	--------
B-1	54	1303	Hawaii Natl. Pk. Hq.	1210	ENE	Weekly	12	Closed 'ohi'a forest	Short-term continuous monitoring of moisture and wind parameters
B-2	45.1	----	Mauna Loa 5500	1692	SE	Weekly	12	Koa parkland	--------
B-3	45.5	----	Mauna Loa T 6600	2012	SE	Weekly	12	Open koa/māmane	Short-term continuous monitoring of under-canopy fog drip and leaf wetness
C-1	26.3	----	Waipunaula	707	W	Monthly	2	Orchards (coffee)	Discontinued (fog absent)
C-2	77.7	----	No. A Pump	1082	W	Monthly	15	Closed 'ohi'a forest	--------
C-3	77.4	----	JP	1082	W	Monthly	15	Open 'ohi'a pastureland	--------
C-4	77.2	----	Pauahi	1317	W	Monthly	15	Open 'ohi'a pastureland	--------
C-5	77	----	Pāpaloa	1561	W	Monthly	15	Open koa pastureland	Short-term continuous monitoring of moisture and wind parameters
C-6	77.1	----	Pāpa'i Clark	1708	W	Monthly	15	Open māmane forest	--------
C-7	77.6	----	Keanakini	2164	W	Bimonthly	15	Māmane subalpine shrub	--------
D-1	70	1557	Hōlualoa	981	WSW	Monthly	14	Open 'ohi'a pastureland	Out of service, March-May 1975
D-2	71	2047	Honua'ula	1905	WSW	Monthly	17	Open koa pastureland	--------
D-3	72	2151	Hualālai (summit)	2496	All	Monthly	17	Subalpine shrub	Periodic monitoring of soil moisture under māmane
E-1	30	----	Kōmakawai	1875	W	Bimonthly	12	Open koa pastureland	--------
E-2			McCandless Reservoir*	2164	W	Bimonthly	12	Open māmane pastureland	Large scale fog net installed

*Unnumbered site.

MOUNTAIN FOG ON MAUNA LOA

As is the case with any climatic analysis, explanation and predictive success are generally proportional to the density of the sampling network and the length of the data collection period. Limitations in the present study relative to these factors have been enumerated in the preceding chapter. While the fog study described in this paper constitutes part of an ongoing project programmed to extend for several additional years, the existing data set appears adequate to fulfill the primary research objective of providing a quantitative description and explanation of the mountain fog regime on Mauna Loa. The presumed representativeness of the data set is primarily based on the recurrence of similar fog patterns in the 1974, 1975, and 1976 data. Subsequent expansion of the data set is viewed useful, primarily for increased refinement of the spatial fog patterns and of fog variability models described in this chapter.

Because of substantial differences in the general climatic environments of windward and leeward Mauna Loa, the fog regimes for these two areas are separately treated here, with comparative analysis reserved for a concluding section.

Windward Mauna Loa

ALTITUDINAL FOG GRADIENT. Rain and fog data for Transect A (Fig. 5) on windward Mauna Loa are available for the period October 1972 through December 1975. The 1972 and 1973 data are incomplete and contain substantial gaps. In a preliminary analysis of the limited data for this earlier period, Juvik and Perreira (1974) confirmed quantitatively the occurrence of a distinctive fog belt on the windward slope at elevations between 1 500 and 2 500 m. Annual rain and fog totals along Transect A for the years 1974 and 1975 are presented in Figure 6. In addition to the absolute values, fog is also expressed in relative terms as a percentage of rainfall. With respect to rain and fog totals, the two years are surprisingly similar, given the normally high annual precipitation variability that is characteristic of the island. For both years, annual rainfall totals did not substantially deviate from the long-term normal (Table 3).

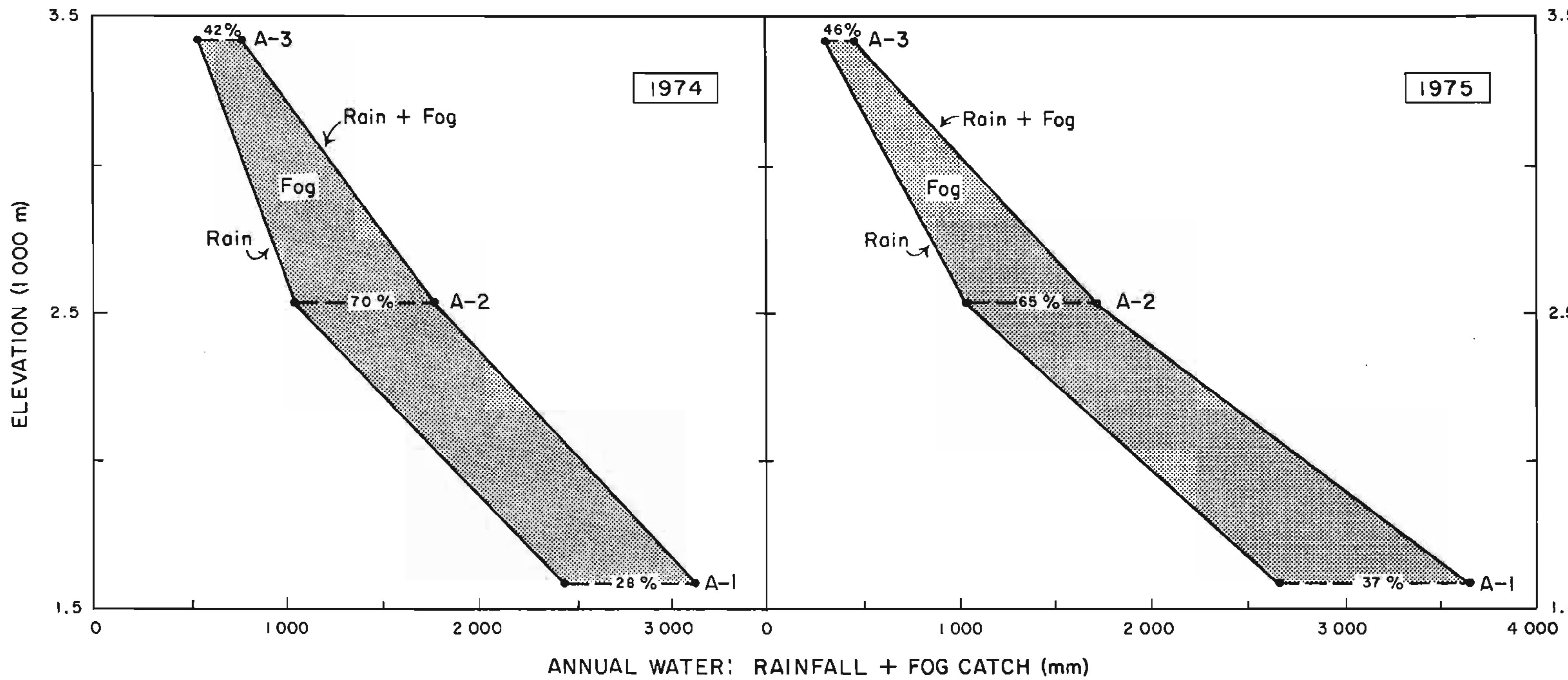


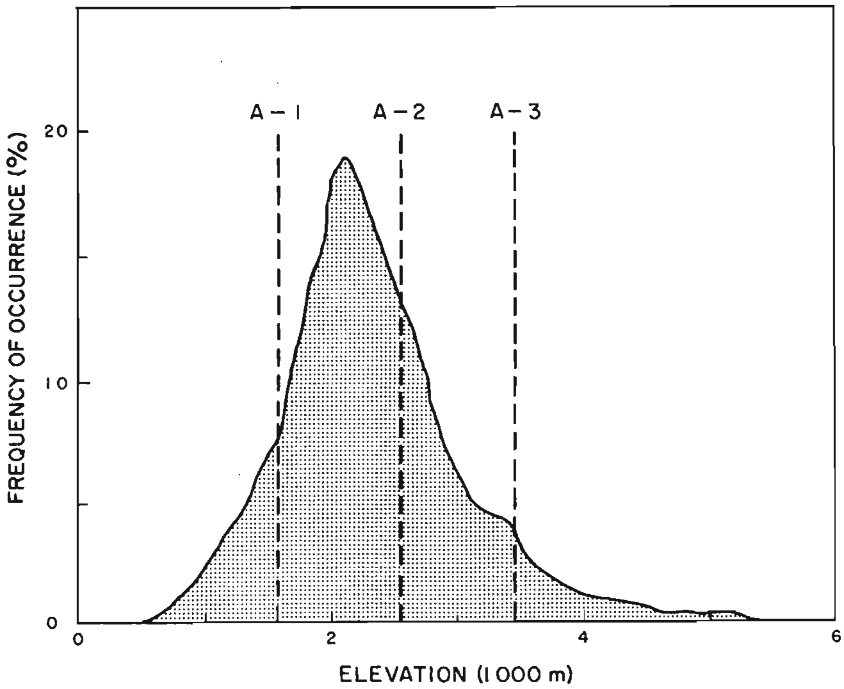
FIGURE 6. CUMULATIVE 1974-1975 RAINFALL AND FOG ON WINDWARD MAUNA LOA, TRANSECT A STATIONS, HAWAI'I ISLAND

TABLE 3. TRANSECT A MONTHLY RAIN AND FOG PRECIPITATION, KŪLANI CAMP, KŪLANI MAUKA, AND MAUNA LOA SLOPE OBSERVATORY, HAWAI'I ISLAND, 1974-1975

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
					A-1, Kūlani Camp (el. 1 580 m)								
1974													
Rain (mm)	222.5	148.8	302.3	511.5	231.6	82.5	52.3	53.3	24.1	219.7	152.6	448.0	2449
Fog (mm)	59.9	33.7	68.7	96.3	86.8	46.8	26.6	38.7	11.1	63.1	50.3	98.6	681
Fog:Rain Ratio	0.27	0.23	0.23	0.19	0.37	0.57	0.51	0.73	0.46	0.29	0.33	0.22	0.28
Rain, % Normal	102	53	95	198	124	108	37	25	22	137	51	171	93
1975													
Rain (mm)	1078.9	326.4	274.6	229.8	82.8	48.3	70.3	74.2	91.9	171.2	163.1	67.0	2679
Fog (mm)	178.3	58.3	14.7	179.1	66.0	63.2	46.7	52.6	46.7	90.3	42.3	21.1	859
Fog:Rain Ratio	0.17	0.18	0.53	0.78	0.80	1.31	0.67	0.71	0.51	0.53	0.26	0.31	0.32
Rain, % Normal	490	116	86	89	44	64	52	38	82	107	55	26	104
					A-2, Kūlani Mauka (el. 2 530 m)								
1974													
Rain (mm)	42.4	72.9	133.8	210.1	66.0	10.4	10.1	33.5	20.1	134.4	58.9	238.3	1031
Fog (mm)	25.4	43.1	135.5	152.1	67.7	20.1	14.7	27.5	11.0	67.1	26.7	143.5	734
Fog:Rain Ratio	0.60	0.59	1.01	0.72	1.03	1.93	1.44	0.82	0.55	0.50	0.45	0.60	0.71
Rain, % Normal	55	72	144	263	115	59	19	36	52	221	66	236	112
1975													
Rain (mm)	506.9	258.3	48.5	48.3	7.1	10.2	19.3	25.3	16.0	36.3	36.8	33.3	1046
Fog (mm)	176.3	113.7	66.5	96.0	22.6	16.5	39.4	35.9	26.9	40.1	29.3	14.6	678
Fog:Rain Ratio	0.35	0.44	1.32	1.99	3.18	1.62	2.03	1.41	1.68	1.10	0.79	0.44	0.65
Rain, % Normal	660	236	54	61	12	57	37	27	41	60	41	33	110
					A-3, Mauna Loa Slope Observatory (el. 3 415 m)								
1974													
Rain (mm)	42.4	6.6	86.8	56.6	50.0	11.2	21.8	20.3	25.1	76.4	26.7	130.0	555
Fog (mm)	25.4	4.3	59.2	16.6	6.7	2.6	4.5	2.1	4.1	39.6	14.0	53.9	233
Fog:Rain Ratio	0.60	0.64	0.68	0.29	0.13	0.23	0.21	0.11	0.16	0.52	0.53	0.41	0.42
Rain, % Normal	79	18	171	111	104	73	72	36	40	177	62	256	100
1975													
Rain (mm)	106.1	127.0	10.4	20.0	0	4.1	4.1	4.8	1.0	5.7	12.7	4.1	300
Fog (mm)	56.3	51.6	7.2	4.6	0	3.8	1.3	1.7	0.8	0.3	4.9	5.1	138
Fog:Rain Ratio	0.53	0.41	0.69	0.23	0	0.83	0.33	0.35	0.79	0.05	0.39	1.25	0.46
Rain, % Normal	199	356	21	40	0	27	13	9	2	13	29	8	65

In 1974 absolute fog interception reached a maximum at Station A-2 (el. 2 530 m) where 731 mm of fog were recorded for the year. Relative fog (percent of rainfall) was also highest at this station (70%). In 1975, Station A-2 again recorded the maximum value for relative fog (65%) although the absolute maximum shifted to A-1 (el. 1 580 m) where 992 mm were recorded. The precipitation gradient on the upper slopes of windward Mauna Loa reflects, to a large extent, the interaction of the orographic uplift and the tradewind inversion. In evaluating the altitudinal variation in fog interception presented in Figure 6, the influence of the tradewind inversion is particularly apparent.

Figure 7 illustrates the frequency of the tradewind inversion base height relative to the elevation of Transect A stations. It should be cautioned, however, that in interpreting Figure 7, the inversion data are derived from free air soundings over Hilo; and the actual height of the inversion base over the inland slopes is, on the average, deflected somewhat upward by the mountain mass (Mendonca and Iwaoka 1969). It can be seen from this figure that Station A-2 lies in the general zone of maximum inversion base frequency, that is, the area where the orographic cloud is



SOURCE: Chin et al. (1971).

FIGURE 7. FREQUENCY DIAGRAM OF THE HEIGHT OF THE BASE TEMPERATURE INVERSION FOR HILO RELATIVE TO THE ELEVATION OF TRANSECT A STATIONS, HAWAI'I ISLAND

narrowly compressed between the rising slope and the inversion lid. The high ratio of fog to rain at Station A-2 is thus expected because at this elevation the inversion frequently hinders vertical cloud development and retards the growth of large raindrops.

The annual fog values for Station A-3 (el. 3 410 m) also reflect the control exerted by the tradewind inversion. From Figure 7 it is evident that this station lies above the inversion more than 95% of the time, and thus, the prospects for either rain or fog are greatly reduced, a fact reflected in the low absolute values (Fig. 6).

The lower relative fog values at A-3 may be explained by the fact that general synoptic disturbances, rather than local orographic effects, are responsible for most of the precipitation at this high elevation. The tradewind inversion is normally destroyed during large-scale disturbances, and, in the absence of an inversion, there would be no particular bias favoring fog over rainfall.

In summarizing the annual totals of rainfall and fog from Transect A, the relative fog contribution appears to reach a maximum at mountain elevations between 2 000 to 3 000 m. The absolute fog maximum occurs somewhat lower on the slope where overall precipitation is greater.

SEASONAL VARIATION IN FOG. Monthly rain and fog values (1974, 1975) for Transect A stations are presented in Table 3. While the annual rainfall and fog totals for the two years show close agreement (Fig. 6), an examination of the monthly data indicates substantial differences between the two years with respect to the seasonal distribution of both rainfall and fog. The year 1975 is characterized by an extremely skewed precipitation distribution with from 50 to 80% of the annual rainfall, depending on station, concentrated in the months of January and February. The remaining ten months are consistently, and often substantially, below normal. A similar pattern is evident in the fog values.

As illustrated in Table 3, the highest absolute fog values occur in those months that also record above-normal rainfall. In such situations the impact of the fog on mountain ecosystems would be minimized due to the lack of any substantial moisture stress. By contrast, there are many relatively dry months where absolute fog values are low, yet substantially higher than the rainfall for the same period. It is during such times that

fog may become an important factor in meeting evapotranspiration demand. For this reason, the monthly fog-to-rain ratio, rather than the absolute fog, is often a more useful term for assessing fog impact.

The 1974 to 1975 monthly fog-to-rain ratios for Transect A stations are presented in Figure 8. The data plot reveals several significant trends and interrelationships:

1. Both Stations A-1 and A-2 show similar seasonal patterns recurrent in both years and characterized by a well-defined summer maximum and winter minimum. The summer maximum is consistent with the increased frequency of the orographic cloud in summer and the generally lower rainfall resulting from greater atmospheric stability imposed by a seasonally stronger and more persistent tradewind inversion.
2. Compared with A-1 and A-2, Station A-3 is distinguished by a complete seasonal reversal, exhibiting a winter maximum and summer minimum (more evident in the 1974 data) in the fog-to-rain ratio. If the 1974 data can be taken as typical, there is clearly an abrupt transformation in seasonal fog occurrence, as well as absolute fog amount, in the mountain elevations between 2 500 and 3 400 m. Again, the most plausible explanation for this phenomenon rests with the location of stations relative to the inversion base height discussed in the preceding section.

   Since the tradewind inversion is best developed in summer at an elevation consistently below Station A-3, the station is effectively cut off from mountain fog associated with the summer orographic cloud. Any precipitation that does reach A-3 in summer normally occurs when the inversion has been destroyed. On such occasions rain may be just as likely to occur as fog.
3. The generally higher values for the fog-to-rain ratio evident in the monthly 1975 data are consistent with an extended period of subnormal rainfall. This relationship suggests that possible efforts to develop an empirical relationship between rain and fog might be enhanced by considering rainfall departure from normal rather than simply the absolute rainfall. These relationships are further explored in the following section.

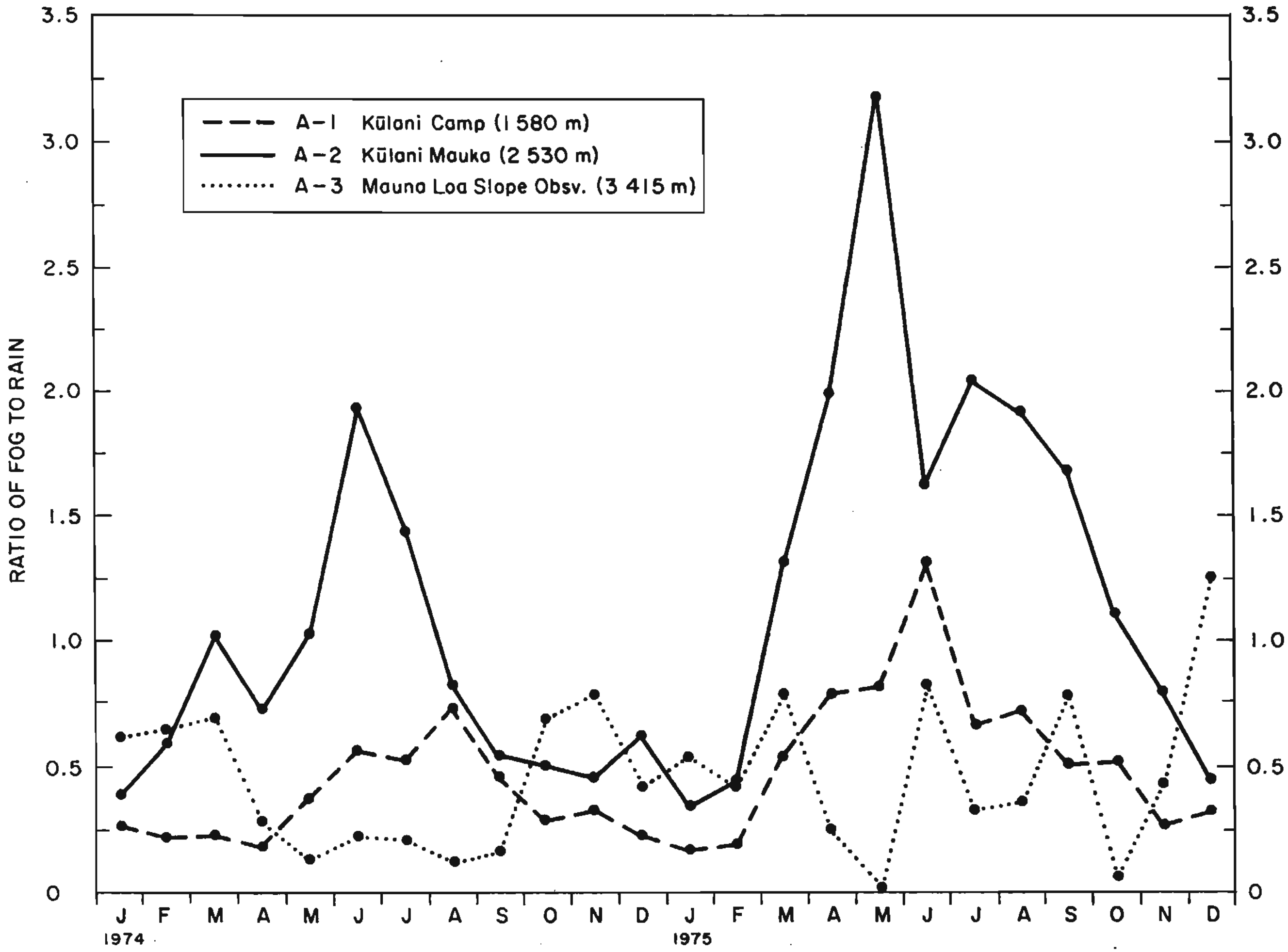


FIGURE 8. SEASONAL VARIATION IN MONTHLY FOG:RAINFALL RATIOS FOR TRANSECT A STATIONS, WINDWARD MAUNA LOA, HAWAI'I ISLAND, 1974-1975

A generalized seasonal profile for windward slope fog has been prepared by extrapolating values for selected elevations intermediate between Stations A-1, A-2, and A-3. Computation of the intermediary values is based on assumed logarithmic spacing of isohyets (with distance) between stations and is derived by weighing the fog-to-rain values from adjacent stations along the transect.

The actual and extrapolated values are presented in Figure 9. The sharp diminution in relative fog and its transformation from a summer to winter maximum regime in the zone above 2 500 m is the most striking feature of the windward fog gradient.

RELATIONSHIP BETWEEN RAINFALL AND FOG. In the Mauna Loa situation, rainfall and fog simply represent different points on a droplet growth continuum associated with the orographic precipitation process. The covariation in monthly rainfall and fog values apparent in the Transect A data (Table 3) may be expected in that, on the higher slopes, general atmospheric conditions favoring precipitation might, through the course of a given episode, produce a droplet spectrum yielding both rain and fog. In a preliminary analysis of the winter 1972 to 1973 data, strong correlations between weekly rain and fog values were found. Figure 10 presents the data scatter and regression equations for the three stations.

With respect to the more complete 1974 to 1975 data, it has been demonstrated in the preceding section that monthly fog-to-rain ratios are characterized by well-defined seasonal trends. Ideally, if sufficient years of data were available, it should be possible to derive a family of 12 monthly regression equations relating fog to rain. However, with but two years (1974-1975) of data, it was necessary to undertake regression analysis on the monthly values grouped into arbitrary summer (April-September) and winter (October-March) periods. This grouping allowed sufficient data points for statistically significant analysis and adequate portrayal of the distinctive seasonal patterns.

In addition, after preliminary analysis certain extreme monthly values, e.g., January 1975, are deleted from the calculations because their inclusion strongly skews the regression analysis, yielding a generally poorer least-squares fit to the cluster of lower, more meaningful values.

Figures 11 to 13 illustrate the winter and summer relationships between monthly rainfall and fog for Transect A stations. With the single exception of the winter datum of 0.553 for Transect Station A-1 (Fig. 11),

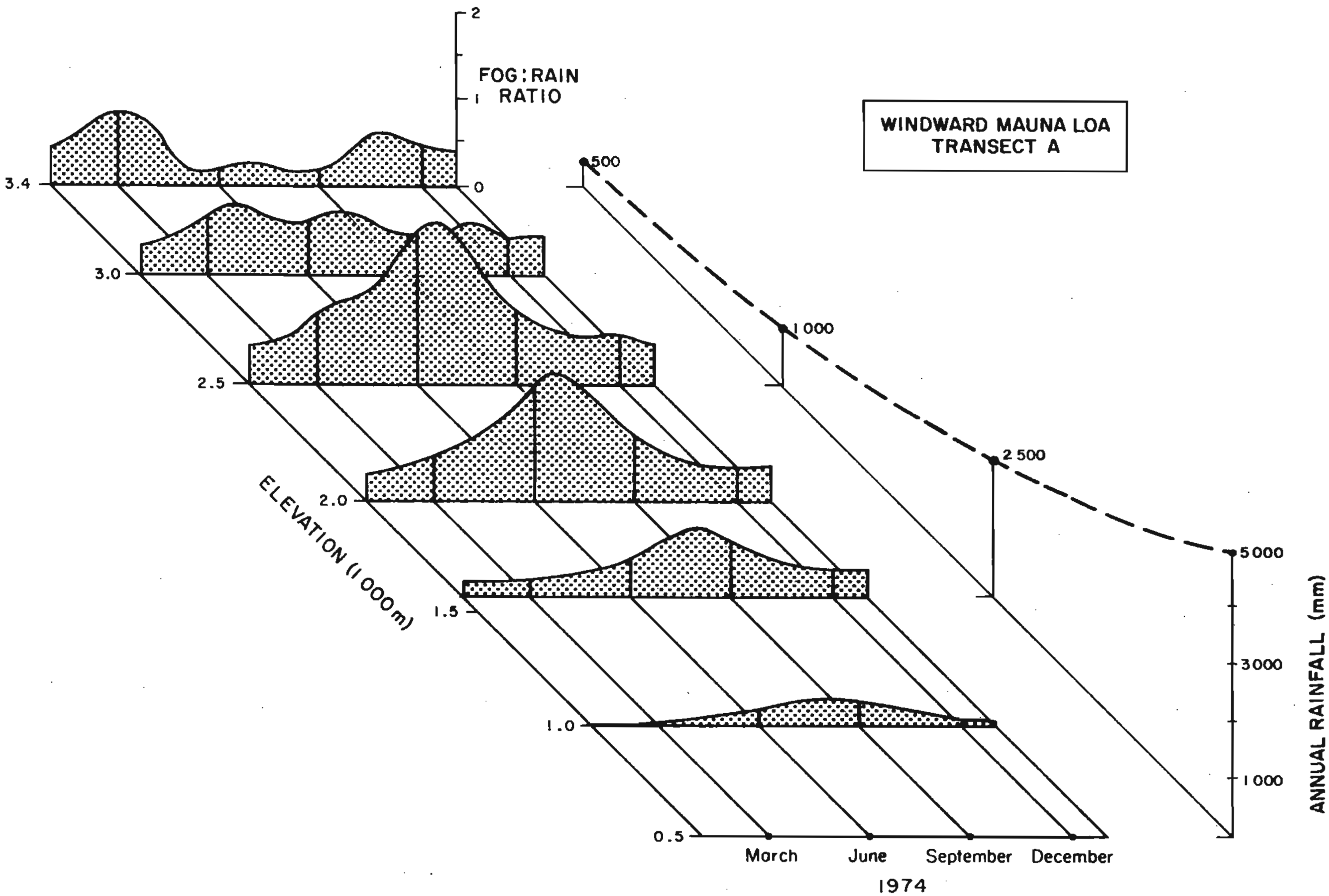


FIGURE 9. GENERALIZED MODEL OF SEASONAL FOG CATCHMENTS ON THE WINDWARD SLOPE OF MAUNA LOA, HAWAI'I ISLAND

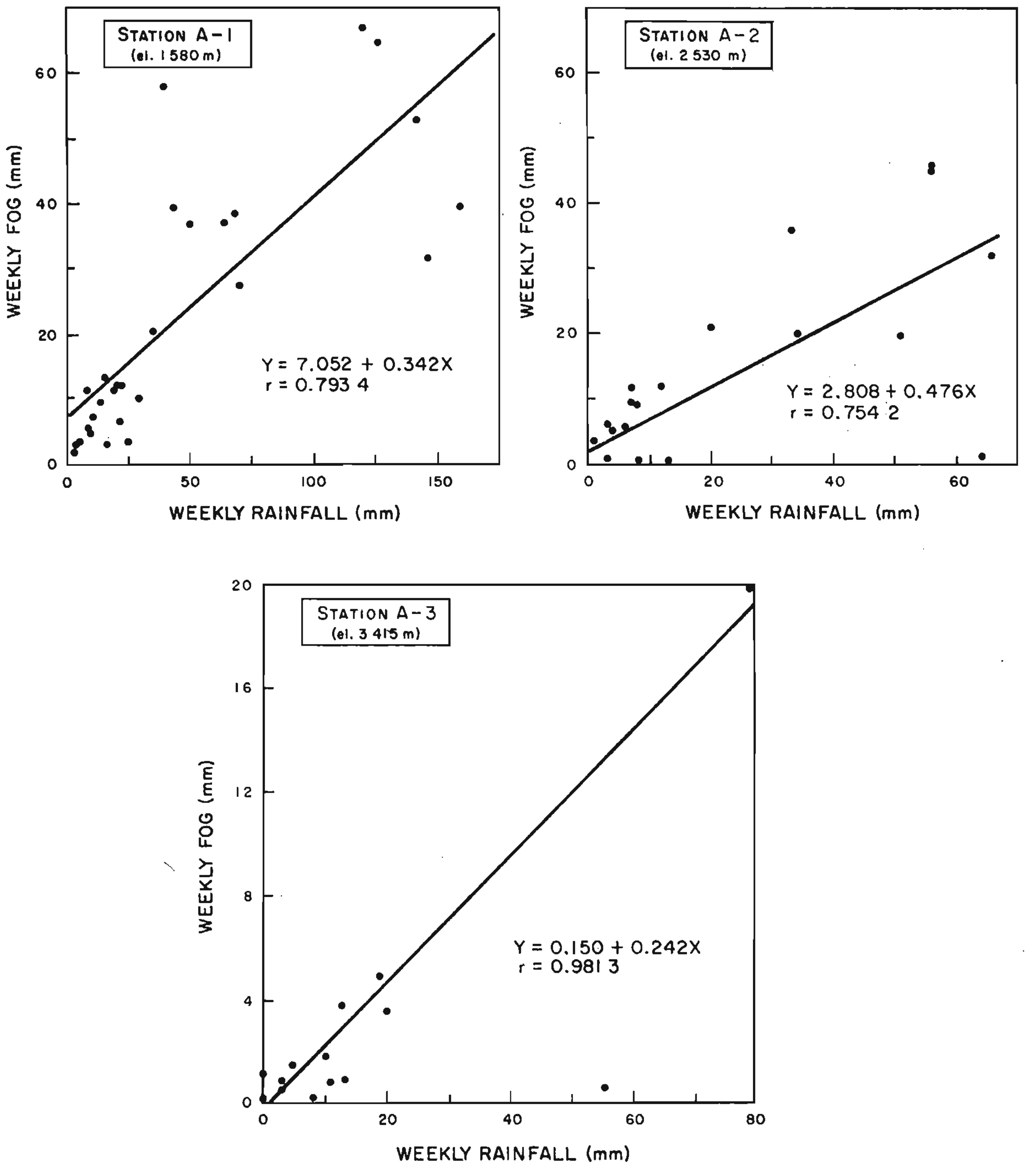


FIGURE 10. RELATIONSHIP BETWEEN WEEKLY RAINFALL AND FOG INTERCEPTION AT TRANSECT A STATIONS ON MAUNA LOA, HAWAI'I ISLAND, OCTOBER 1972-APRIL 1973

both the summer and winter coefficients of Figures 11 to 13 range from 0.816 to 0.947, confirming that seasonal fog can be realistically predicted from simple rain values alone. The slope values in the seasonal regression equations can be interpreted as roughly approximate to the mean winter or summer fog-to-rain ratios and are consistent with the data presented in Figure 8.

Based on the monthly data in Table 3, it appears that rainfall departure from normal exerts some effects on the relative partitioning of precipitation between rain and fog. It can be assumed that periods of unseasonably low rainfall are characterized by conditions of atmospheric stability in which rain would be much less likely to occur. As an example, consistently higher fog-to-rain ratios are associated with the extended low rainfall period in 1975. Based on this apparent covariation, it was considered that an overall improvement in fog-to-rain prediction might be attained by inclusion of a rainfall departure term in addition to the absolute rainfall values.

While it is recognized that a data set representing long-term observations would be required for any definitive evaluation of the rainfall departure term relative to the fog-to-rain ratio, a preliminary treatment

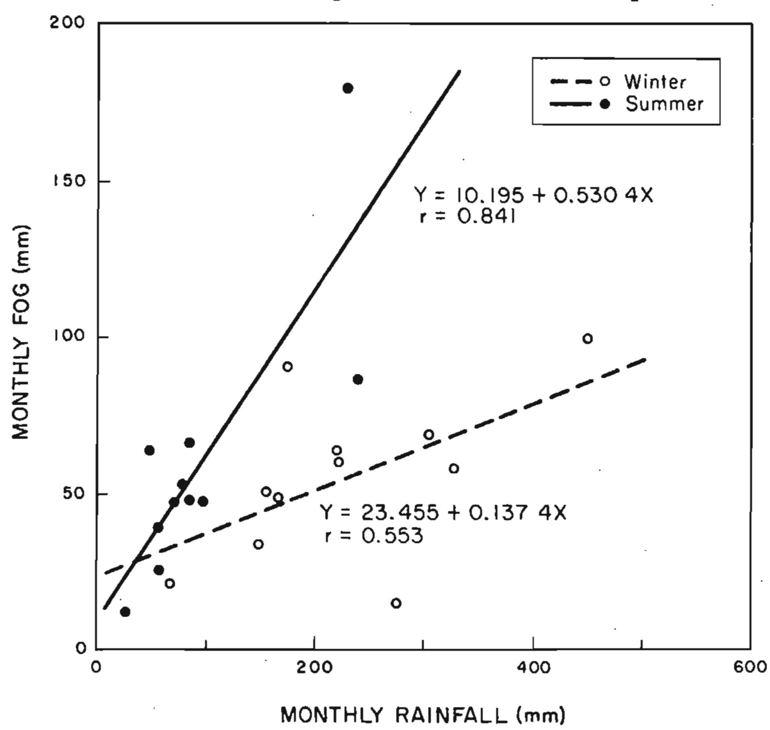


FIGURE 11. RELATIONSHIP BETWEEN RAINFALL AND FOG AT KŪLANI CAMP (A-1) STATION, HAWAI'I ISLAND, 1974-1975

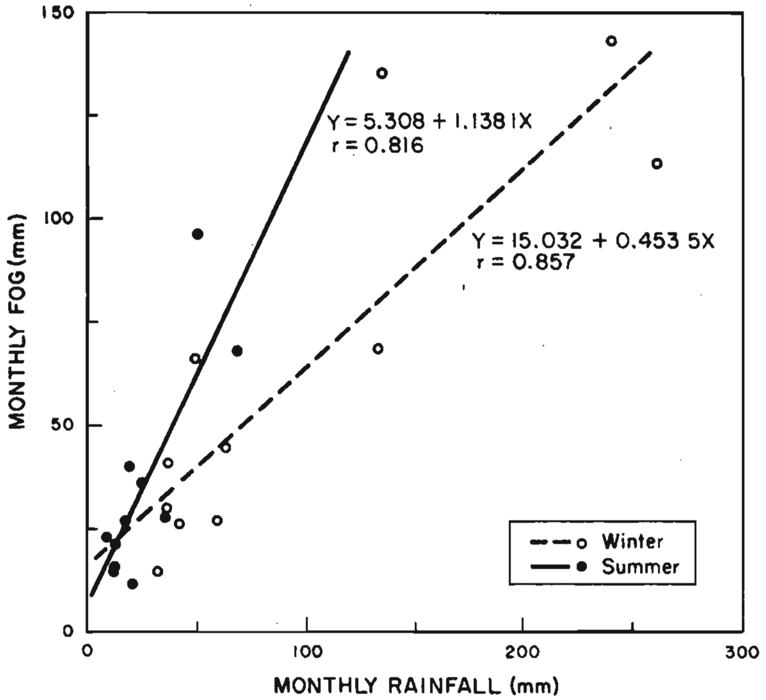


FIGURE 12. RELATIONSHIP BETWEEN RAINFALL AND FOG AT KŪLANI MAUKA (A-2) STATION, HAWAI'I ISLAND, 1974-1975

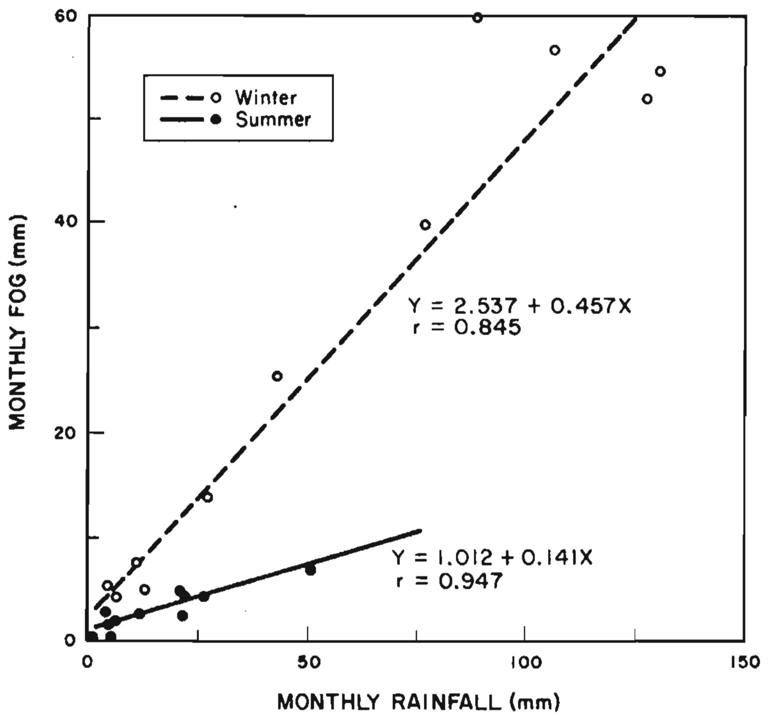


FIGURE 13. RELATIONSHIP BETWEEN RAINFALL AND FOG AT MAUNA LOA SLOPE OBSERVATORY (A-3) STATION, 1974-1975

of the summer data for Station A-2, analyzed by linear regression in Figure 12, does suggest that inclusion of this term might well improve fog prediction.

Figure 14 presents the monthly fog-to-rain ratios plotted against rainfall departure for Station A-2.

Since the fog-to-rain ratio would approach zero under conditions of extremely high rainfall and infinity under conditions of extremely low rainfall, in theory the data should be best defined by a hyperbolic function of the basic form $Y = 1/X$. In general, the data appear to fit this relationship. A best-fit hyperbolic function derived by successive approximation takes the form, $Y = 0.81/X^3$, where Y = the monthly fog-to-rain ratio and X is the rainfall departure. The regression coefficient derived from this equation was 0.698, somewhat lower than the value of 0.816 for the simple linear regression coefficient for summer rain and fog at Station A-2 (see Fig. 12). The standard error of the estimate is, however, usually a better indication of the predictive power of an equation than the regression coefficient. If the equation above is solved for fog, rather than for fog to rain, the standard error of the fog estimate (10.06 mm) is slightly better

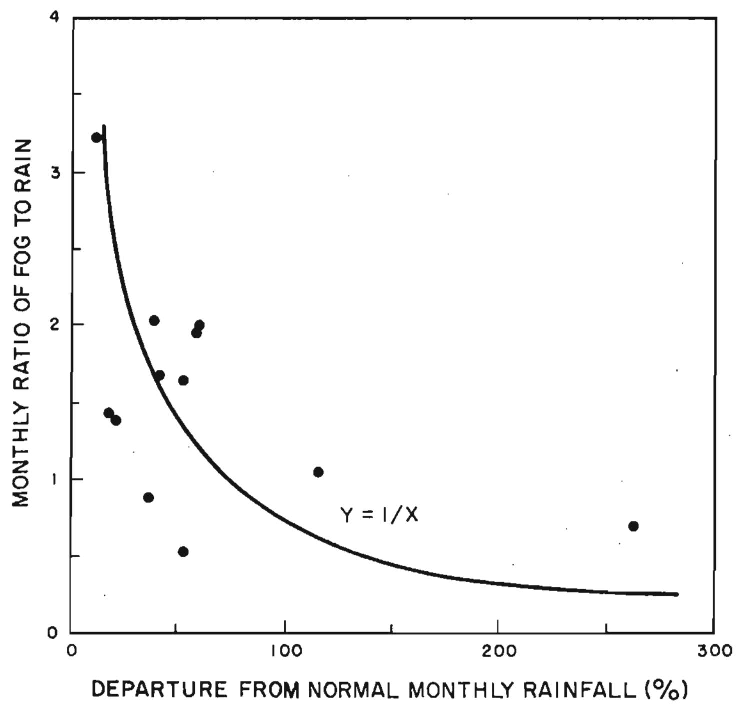


FIGURE 14. RELATIONSHIP BETWEEN MONTHLY RAINFALL DEPARTURE FROM NORMAL AND THE FOG:RAIN RATIO, KŪLANI MAUKA (A-2) STATION, HAWAI'I ISLAND, SUMMER 1974-1975

than the standard error for the simple linear relationship between fog and rain (10.14 mm). Based on this preliminary assessment it would appear that, given an extended data set, a family of hyperbolic curves (for seasons or indiviudal months) relating the fog-to-rain ratio to rainfall departure may ultimately prove a powerful tool for the prediction of mountain fog.

MOUNTAIN FOG AND THE TRADEWIND INVERSION. The role of the tradewind inversion has been repeatedly stressed as an important factor in the foregoing explanation of altitudinal and seasonal fog variation. In an effort to refine and quantify these relationships, a statistical analysis was undertaken of inversion dynamics in relation to the occurrence of rain and fog episodes. This analysis must be characterized as provisional and tentative to the extent that several limitations in the data set preclude a comprehensive assessment.

The National Weather Service records upper-air data from twice-daily (at 0100 hr and 1300 hr) radiosonde ascents over Hilo. Corresponding daily rain and fog values are only available for Station A-1. For Stations A-2 and A-3, fog and rain data were collected on a weekly basis. Station A-1 is located at an elevation well below the normal inversion base height and the zone of maximum fog; however, insofar as it is the only station with daily rain and fog values, an analysis of precipitation relationships with the tradewind inversion was undertaken utilizing an existing upper-air, computerized data deck made available by the University of Hawaii Cloud Physics Laboratory. The data include twice-daily readings of tradewind inversion base height and strength for September through December 1974. The twice-daily readings are averaged to give a single daily value for correlation with the daily fog-to-rain ratios for the corresponding period at Station A-1. The data were subjected to both linear and curvilinear (log-log) regression analysis. The monthly and total period correlation coefficients are presented in Table 4.

The results indicate a very low correlation between inversion base height and the fog-to-rain ratio. The predominance of negative values for the correlation of the fog-to-rain ratio with inversion height does conform to the thesis that fog is more likely than rain when both the inversion height and the precipitable water in the air are low. The use of the log-log transformation of the regression equation has but minor advantage over

the linear regression line to show the relationship between the daily inversion base height and the fog-to-rain ratio (Fig. 15).

TABLE 4. CORRELATION COEFFICIENTS FOR DAILY RAIN, FOG, AND INVERSION PARAMETERS, SEPTEMBER-DECEMBER 1974, KŪLANI (A-1) STATION, HAWAI'I ISLAND

VARIABLES CORRELATED	REGRESSION COEFFICIENTS Sept. (n = 11)	Oct. (n = 21)	Nov. (n = 20)	Dec. (n = 24)	Total (n = 76)
Fog:Rain with Inversion Height	.1813	-.3068	-.3450	-.4421	-.1857
Log (Fog:Rain) with Log Inversion Height	.3035	-.2475	-.2523	-.5145	-.2224
Fog:Rain with Inversion Strength	-----	-----	-----	-----	-----
Rain with Fog	-.1845	.9157	.3610	.8346	.8229

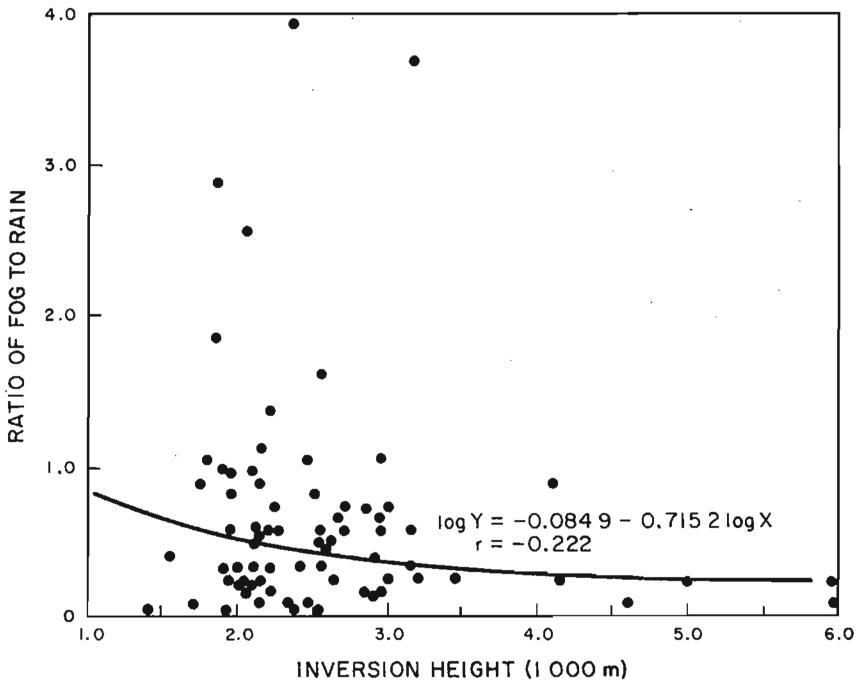


FIGURE 15. RELATIONSHIP BETWEEN DAILY INVERSION HEIGHT AND THE FOG:RAIN RATIO, KŪLANI CAMP (A-1) STATION, HAWAI'I ISLAND, SEPTEMBER-DECEMBER 1974

Rainfall has been shown to have a strong positive correlation with inversion height (Fullerton and Wilson 1974), so that the ratio of fog to rain (proportional to $\frac{1}{\text{rainfall}}$) would be expected to have a negative

correlation with inversion height found in this study. However, rainfall has also been shown to be negligible when the inversion height is below 2 000 m.

The correlation of fog-to-rain ratio with the inversion strength also is very low, but positive. This again conforms to the thesis that there is relatively more fog than rain when the air has greater stability.

The actual daily amounts of rainfall and fog catch for the entire 4-mo period show a very high positive correlation, although the correlations for September alone were low and negative. This unusual, high positive correlation suggests that the amounts of rain and fog catch parallel one another.

The rain, fog, and inversion height measurements for May, June, July, and September 1975 for Station A-1 are also analyzed (Table 5). Daily rainfall is segregated into two groups, one with daily rainfall of <2.54 mm and the second with daily rainfall of ≥2.54 mm. The separation presumes that on days with <2.54 mm of rainfall, mountain fog interception is the dominant source of water. Ekern (1964) found on Lāna'ihale that the ratio of fog to rain for low rainfall intensity days (<2.54 mm) averages 2.75, compared to a ratio of only 0.3 for heavier rainfall periods (>2.54 mm/day).

For the 50 summer days with rainfall below 2.54 mm, the mean ratio of fog to rain is 1.75 compared to a ratio of 0.53 for the 29 days where rainfall intensities exceed 2.54 mm. Of the total 290.56 mm of rainfall, 53.08 mm or 18.3% is in the light rainfall group. In contrast, 92.69 mm or 43.3% of the total summer fog interception occurred during the light rainfall periods. The average height of the tradewind inversion is 2 110 m for the light rainfall periods but rises to 2 580 m for the periods of heavier rainfall.

The results for 1975 agree with the general trends for 1974. During low rainfall periods, both the amount of fog catch and the fog-to-rain ratio increase when the inversion height decreases (Fig. 16). For the heavier rainfall periods, the fog catch also increases when the inversion height decreases, except for the month of June. For June and July, with fully developed tradewinds, the amounts of fog catch are nearly independent of the rainfall character.

Only mean weekly values for fog catch are available for Station A-2 in the peak fog belt. The average weekly inversion height may not closely correspond to the height during the fog catch since the height fluctuates

TABLE 5. SUMMER 1975 PRECIPITATION AND INVERSION HEIGHT SEGREGATED BY RAINFALL INTENSITY, KŪLANI CAMP (A-1) STATION, HAWAI'I ISLAND

Month	Sample Size (days)	Rain mm/period (mm/day)	Fog mm/period (mm/day)	Fog: Rain Ratio	Inversion Height (m)
		DAYS WITH RAINFALL INTENSITIES <2.54 mm/day			
May	10	11.18 (1.12)	23.89 (2.39)	2.13	2 080
June	15	13.46 (0.89)	33.79 (2.25)	2.51	2 060
July	15	16.26 (1.08)	22.31 (1.49)	1.37	2 140
Sept.	10	12.19 (1.22)	12.71 (1.27)	1.04	2 180
TOTAL PERIOD	50	53.09 (1.08)	92.70 (1.85)	1.76	2 120
		DAYS WITH RAINFALL INTENSITIES >2.54 mm/day			
May	9	72.89 (8.10)	43.47 (4.83)	0.59	2 530
June	6	30.73 (5.12)	28.29 (4.71)	0.92	2 330
July	5	54.10 (10.82)	21.52 (4.30)	0.39	2 900
Sept.	9	79.76 (8.86)	33.68 (3.74)	0.42	2 660
TOTAL PERIOD	29	237.48 (8.23)	126.96 (4.40)	0.58	2 610

NOTE: Averages in parentheses.

from day to day. The relationship between fog-to-rain ratio and inversion height for the winter season, October 1972 through April 1973, is given in Figure 17. For 10 of the 28 weeks there is either no rain or no fog, so a ratio between them is not possible. The negative correlation coefficient (-0.576) again conforms to the relationship present for the summer months of 1974 and 1975 at Station A-1. The inversion height again forms an essential component for predictive models of mountain fog.

MULTIVARIABLE MODEL FOR DAILY FOG. A reliable model for the prediction of mountain fog would be extremely useful to evaluate the economic feasibility of mountain fog catchment systems and the management of forest

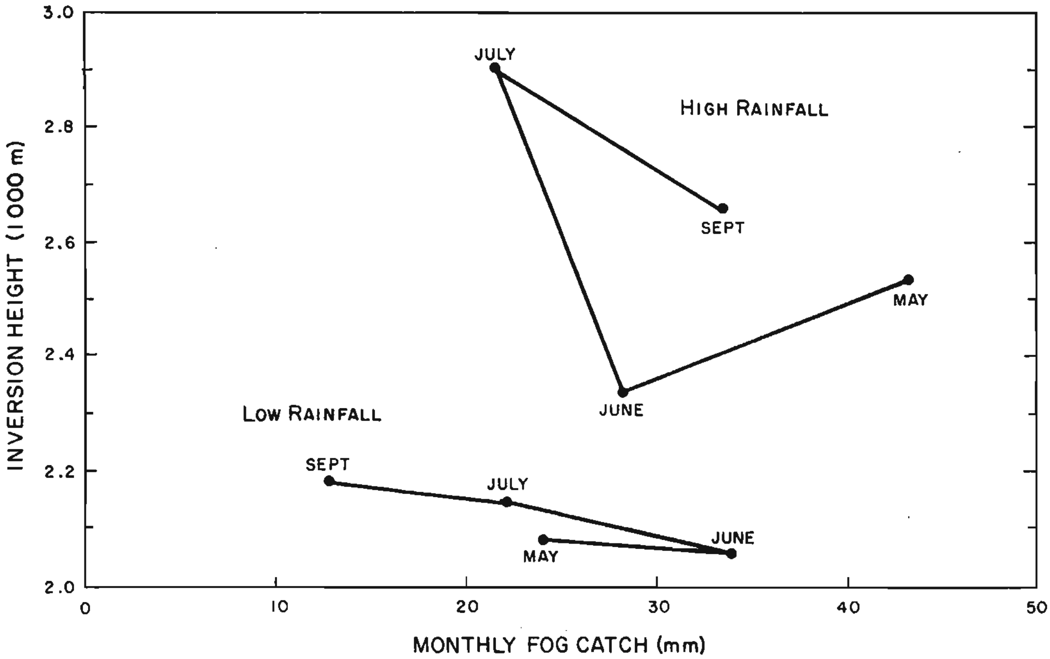


FIGURE 16. RELATIONSHIP BETWEEN INVERSION HEIGHT AND MONTHLY FOG CATCH FOR PERIODS OF LOW RAINFALL (<2.54 mm/day) AND HIGH RAINFALL (>2.54 mm/day) AT KŪLANI CAMP (A-2) STATION, HAWAI'I ISLAND, SUMMER 1975

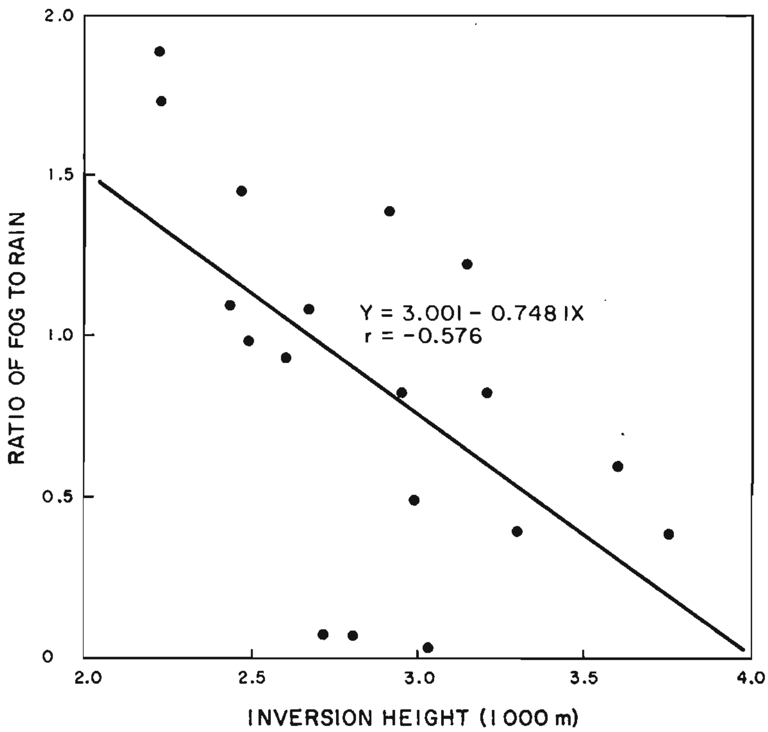


FIGURE 17. RELATIONSHIP BETWEEN INVERSION HEIGHT (MEAN WEEKLY) AND THE FOG:RAINFALL RATIO AT KŪLANI MAUKA (A-2) STATION, HAWAI'I ISLAND, 1972-1973

watersheds. In the preceding sections, empirical relationships between monthly fog, rain, inversion parameters, and elevation demonstrate a potential for gross (monthly and annual) fog prediction from readily available climatic and topographic data.

On the strength of that success, the development of an empirical model for daily fog, utilizing the step-wise multiple regression analysis, was initiated.

Daily rain and fog data were available for Kūlani Camp (Sta. A-1), as well as complete upper-air data (twice-daily radiosonde ascents from Hilo) for the 10-mo period, January through October 1976.

In the analysis fog is specified as the dependent variable and regressed on rainfall and 33 additional variables generated from the upper-air data. These variables are listed in Table 6. Three sets of correlation coefficients and multiple regression equations are derived for the afternoon (0000 hr GMT), nighttime (1200 hr GMT), and combined upper-air data. The results of this analysis are presented in Table 7. The strongest multiple regression coefficient (0.776) is associated with the 1200 hr GMT upper-air data, where rainfall, the ratio of the 1 000- and 3 000-m mixing ratios, wind direction at 1 000 m, and wind speed at 1 000 and 2 000 m account for 60.2% of the explained variation in fog.

Since fog has been shown to be more important during the summer months, particularly on the windward slopes, daily data for June, July, and August 1976 are analyzed to determine the strength of "summer only" relationships between fog, rain, and upper-air parameters.

The correlation coefficients and multiple regression equations for summer fog are presented in Table 8. The strongest multiple regression coefficient (0.851) is obtained from the 0000 hr GMT (1400 hr LT) upper-air data. This is to be expected since the afternoon upper-air data correspond to the period of maximum development of the summer orographic cloud. The variables of rain, 2 000-m mixing ratio, lapse rate, wind speed at 1 000 m, and the 3 000-m mixing ratio account collectively for 72.4% of the variation in daily fog. For the January to October period (Table 7), rainfall alone accounts for 0.50/0.568 or 88% of the explained variation in fog; for the summer period, rainfall alone is 0.58/0.724 or 81% of the explained variation. Thus, all the upper-air parameters add only 12% to the explanation for the year or 14% to the explanation of the summer variation in fog

TABLE 6. VARIABLE LIST, RAINFALL AT KŪLANI CAMP (A-1) STATION AND UPPER-AIR DATA (HILO RADIOSONDE ASCENTS), HAWAI'I ISLAND

Variable Number	Computer Symbol	Explanation
1	RAIN	24-hr total
2	LP-0	Lapse rate between 1 000-2 000 m at 0000 hr, GMT
3	LP-12	Lapse rate between 1 000-2 000 m at 1200 hr, GMT
4	LP-M	Mean lapse rate of 0000 and 1200 hr, GMT
5	B-0	Inversion base height at 0000 hr, GMT
6	B-12	Inversion base height at 1200 hr, GMT
7	B-M	Mean inversion base height of 0000 and 1200 hr values
8	ST-0	Inversion strength at 0000 hr, GMT
9	ST-12	Inversion strength at 1200 hr, GMT
10	ST-M	Mean inversion strength of 0000 and 1200 hr values
11	M1-0	Mixing ratio at 1 000 m at 0000 hr, GMT
12	M1-12	Mixing ratio at 1 000 m at 1200 hr, GMT
13	M1-M	Mean mixing ratio of 0000 and 1200 hr values
14	M2-0	Mixing ratio at 2 000 m at 0000 hr, GMT
15	M2-12	Mixing ratio at 2 000 m at 1200 hr, GMT
16	M2-M	Mean mixing ratio of 0000 and 1200 hr values
17	M3-0	Mixing ratio at 3 000 m at 0000 hr, GMT
18	M3-12	Mixing ratio at 3 000 m at 1200 hr, GMT
19	M3-M	Mean mixing ratio of 0000 and 1200 hr values
20	M1/M3-0	Ratio of 1 000 and 3 000 m mixing ratios at 0000 hr, GMT
21	M1/M3-12	Ratio of 1 000 and 3 000 m mixing ratios at 1200 hr, GMT
22	M1/M3-M	Mean mixing ratios of 0000 hr and 1200 hr values
23	D1-0	Wind direction at 1 000 m at 0000 hr, GMT
24	D1-12	Wind direction at 1 000 m at 1200 hr, GMT
25	D1-M	Mean wind direction of 0000 hr and 1200 hr values
26	D2-0	Wind direction at 2 000 m at 0000 hr, GMT
27	D2-12	Wind direction at 2 000 m at 1200 hr, GMT
28	D2-M	Mean wind direction of 0000 hr and 1200 hr values
29	S1-0	Wind speed at 1 000 m at 0000 hr, GMT
30	S1-12	Wind speed at 1 000 m at 1200 hr, GMT
31	S1-M	Mean wind speed of 0000 hr and 1200 hr values
32	S2-0	Wind speed at 2 000 m at 0000 hr, GMT
33	S2-12	Wind speed at 2 000 m at 1200 hr, GMT
34	S2-M	Mean wind speed of 0000 hr and 1200 hr values

NOTE: Greenwich Mean Time (GMT) - 1000 = Local Time (LT).

TABLE 7. CORRELATION COEFFICIENTS AND MULTIPLE REGRESSION EQUATIONS FOR DAILY FOG (STA. A-1) AGAINST RAINFALL AND UPPER-AIR PARAMETERS, JANUARY-OCTOBER 1976, HAWAI'I ISLAND

Correlation Coefficients for 0000 hr GMT Upper-Air Data

VARIABLES

	RAIN	LP-0	B-0	ST-0	M1-0	M2-0	M3-0	M1/M3-0	D1-0	D2-0	S1-0	S2-0
FOG	0.707	-0.103	0.154	-0.081	-0.078	0.227	0.103	-0.344	-0.130	-0.059	0.466	0.258

Multiple Regression Equation:

FOG = 0.885 + 0.205 (RAIN) + 0.174 (S1 - 0) - 0.008 (D1 - 0) + 0.237 (ST - 0) - 0.087 (S2 - 0)

Multiple r = 0.754
Explained variation (r^2) = 56.8%

Correlation Coefficients for 1200 hr GMT Upper-Air Data

VARIABLES

	RAIN	LP-12	B-12	ST-12	M1-12	M2-12	M3-12	M1/M3-12	D1-12	D2-12	S1-12	S2-12
FOG	0.707	0.062	0.165	-0.092	-0.073	0.857	-0.044	-0.816	-0.136	-0.019	0.304	0.050

Multiple Regression Equation:

FOG 0.383 + 0.218 (RAIN) + 0.218 (M1/M3 - 12) - 0.008 (D1 - 12) + 0.121 (S1 - 12) - 0.099 (S2 - 12)

Multiple r = 0.776
Explained variation (r^2) = 60.2%

Correlation Coefficients for Mean of 0000 hr and 1200 hr GMT Upper-Air Data

VARIABLES

	RAIN	LP-M	B-M	ST-M	M1-M	M2-M	M3-M	M1/M3-M	D1-M	D2-M	S1-M	S2-M
FOG	0.707	0.031	0.187	-0.099	-0.086	0.187	0.033	-0.733	-0.133	-0.039	0.041	0.139

Multiple Regression Equation:

FOG = -1.560 + 0.214 (RAIN) + 0.246 (M1/M3 - M) + 0.244 (S1 - M) - 0.152 (S2 - M) + 0.163 (ST - M)

Multiple r = 0.772
Explained variation (r^2) = 59.6%

NOTE: See Table 6 for variables.
NOTE: Greenwich Mean Time (GMT) - 1000 = Local Time (LT).

TABLE 8. CORRELATION COEFFICIENTS AND MULTIPLE REGRESSION EQUATIONS FOR DAILY FOG AGAINST RAINFALL AND UPPER-AIR PARAMETERS, COMBINED JUNE, JULY, AUGUST 1975 DATA, KŪLANI CAMP (A-1) STATION, MAUNA LOA, HAWAI'I ISLAND

Correlation Coefficients for 0000 hr GMT Upper-Air Data

VARIABLES

	RAIN	LP-0	B-0	ST-0	M1-0	M2-0	M3-0	M1/M3-0	D1-0	D2-0	S1-0	S2-0
FOG	0.764	-0.360	0.372	-0.165	0.202	0.449	0.193	0.000	-0.137	0.139	0.415	-0.061

Multiple Regression Equation:

FOG = 3.613 + 0.346 (RAIN) + 0.151 (M2 - 0) - 0.582 (LP - 0) + 0.186 (S1 - 0) - 0.245 (M3 - 0)

Multiple r = 0.851
Explained variation (r^2) = 72.4%

Correlation Coefficients for 1200 hr GMT Upper-Air Data

VARIABLES

	RAIN	LP-12	B-12	ST-12	M1-12	M2-12	M3-12	M1/M3-12	D1-12	D2-12	S1-12	S2-12
FOG	0.764	-0.101	0.291	0.015	0.109	0.283	0.141	-0.053	-.159	-0.217	0.119	-0.061

Multiple Regression Equation:

FOG = 3.903 + 0.407 (RAIN) - 0.009 (D1 - 12) - 0.114 (S2 - 12) - 0.006 (D2 - 12) - 0.174 (M3 - 12)

Multiple r = 0.820
Explained variation (r^2) = 67.2%

Correlation Coefficients for Mean of 0000 hr and 1200 hr GMT Data

VARIABLES

	RAIN	LP-M	B-M	ST-M	M1-M	M2-M	M3-M	M1/M3-M	D1-M	D2-M	S1-M	S2-M
FOG	0.764	-0.303	0.399	-0.081	0.183	0.455	0.197	-0.035	-0.148	-0.045	0.336	-0.142

Multiple Regression Equation:

FOG = 2.781 + 0.394 (RAIN) + 0.273 (M2 - M) - 0.381 (M3 - M) - 0.476 (LP - M) + 0.184 (ST - M)

Multiple r = 0.826
Explained variation (r^2) = 68.2%

NOTE: Greenwich Mean Time (GMT) - 1000 = Local Time (LT).

amounts and exhibit no clear pattern of individual importance in the various regression equations.

The relationship between fog interception (both daily and monthly) and the upslope vapor flux over Hilo is also investigated; however, there is no significant covariation.

It should be reiterated, however, that the analysis is based on data from Station A-1 located at an elevation of 1 580 m, well below the maximum fog zone on Mauna Loa. It might be expected that, for stations at higher elevation, the upper-air data would exhibit increased explanatory power, particularly at elevations near the base of the tradewind inversion.

CROSS-SLOPE VARIATION IN FOG. The foregoing analysis of windward Mauna Loa fog is exclusively based on Transect A data. As a result of the inaccessibility of Mauna Loa's upper slopes, it is not feasible to establish additional fog sampling transects parallel to A over the extensive altitudinal range involved. Thus, the validity of any cross-slope extrapolations from Transect A results are quantitatively unsupported and should be approached with caution, particularly in view of the rather complex cross-slope variations evident in the annual isohyets on windward Mauna Loa (Fig. 18).

To provide a limited cross check of the Transect A data, fog interception was monitored along Transect B (Fig. 5). Transect A and B stations are not ideally situated for comparison since the altitudinal range of the Transect B stations (from 1 200-2 100 m) overlaps only slightly with those of Transect A (1 600-3 400 m).

Table 9 presents rainfall and fog data for the Transect B stations covering a 9-mo period between June 1974 and June 1975 (January through

TABLE 9. TRANSECT B TOTAL RAINFALL AND FOG CATCHMENT JUNE 1974-JUNE 1975

Station	El. (m)	Rain	Fog	Fog:Rain Ratio
		------(mm)------		
B-1	1.2	1794	381	0.212
B-2	1.65	588	21	0.036
B-3	2.04	644	17	0.026

NOTE: No data for January-March 1975.

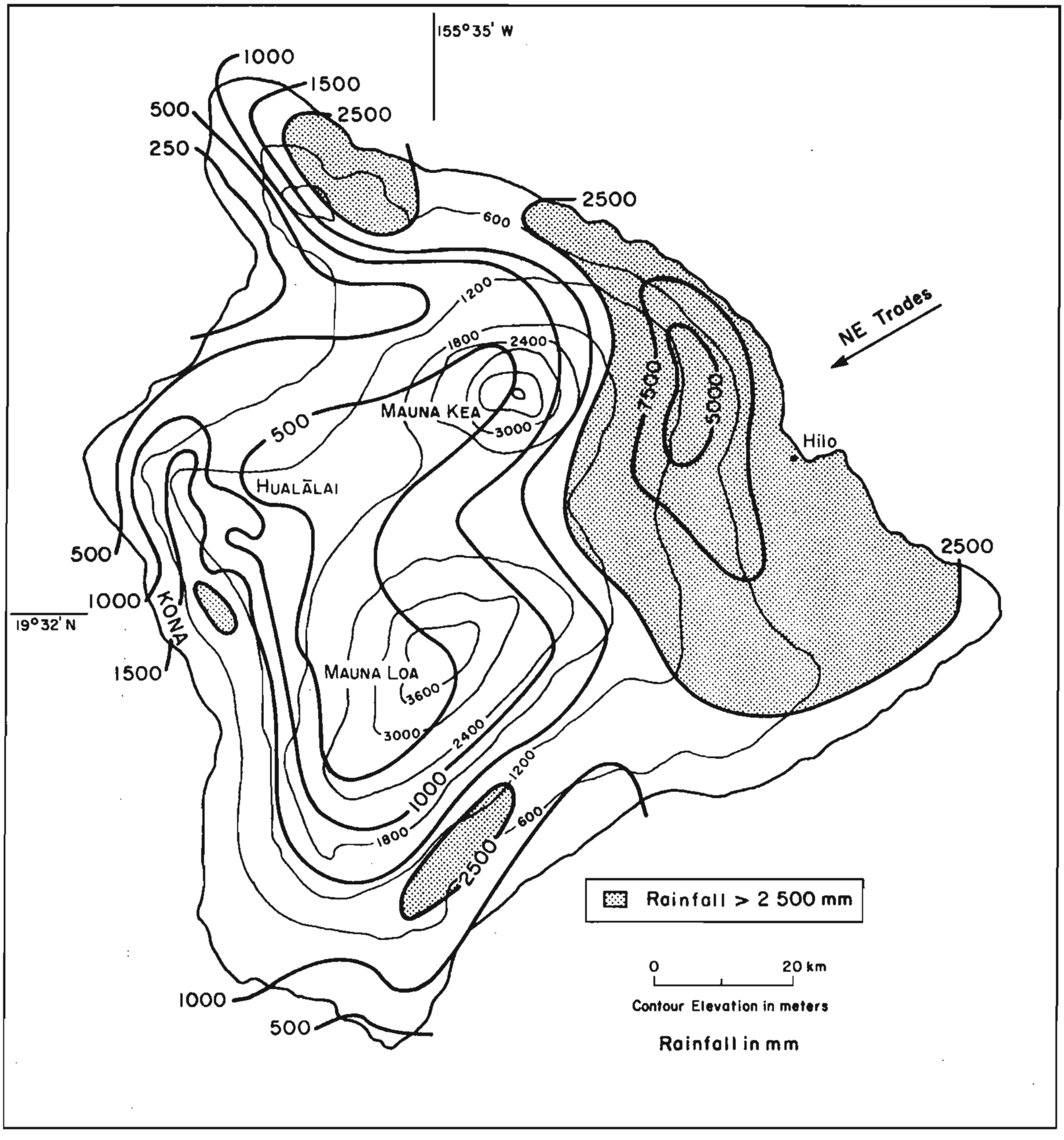


FIGURE 18. ANNUAL RAINFALL DISTRIBUTION ON HAWAI'I ISLAND

March 1975 excluded because of missing data). The virtual absence of fog catch at Stations B-2 and B-3 is the most striking feature of the Transect B data. Instead of increasing with elevation, as was the case for Transect A, both absolute and relative fog decrease up slope along Transect B.

Figure 19 illustrates the plot of the total period fog to rainfall ratio against elevation for both Transect A and B stations. For those elevations in which the two transects overlap, there is a total lack of correspondence in the data.

Only Station B-1 appears to show a reasonable agreement with Transect A in that the data point falls almost exactly on a hypothetical extension of the line connecting Stations A-1 and A-2. If B-1 is assumed to represent a valid extension of Transect A, it is pertinent to assess the general summer fog relationships between Stations B-2 and A-1. For the three summer months (June-August 1975), Station A-1 received 193 mm of rainfall while B-1 (located approximately 400 m lower on the slope) recorded 230 mm, or 19% more rainfall. For the same period the B-1 fog interception equaled 84 mm, or little more than half of the 162 mm received at A-1. These data indicate that the contribution of fog from the summer orographic cloud increases dramatically in the altitudinal zone between 1 000 and 1 500 m.

An explanation for the divergence between the Transect A and B data for the zone of overlap in Figure 19 may rest with the location of the stations relative to the general position of the windward orographic cloud. Based on the distribution of annual isohyets (Fig. 18), Stations B-2 and B-3 appear to lie outside the general zone of high orographic rain frequency. The low fog values suggest that this is especially the case during the summer months.

To better assess differences in the precipitation regimes, an analysis was undertaken of annual and summer rainfall characteristics at Stations A-1, B-2, and a third immediate station between the two transects in the Kīlauea Forest Reserve. All three stations lie at approximately the same elevation (1 580-1 650 m). An examination of the horizontal rainfall gradient between these three stations provides a graphic picture of the sharp change in the precipitation regime that occurs at the margin of the summer orographic cloud. Figure 20 depicts the horizontal gradient for annual and summer rainfall (June-August) as a percentage of the Station A-1 totals.

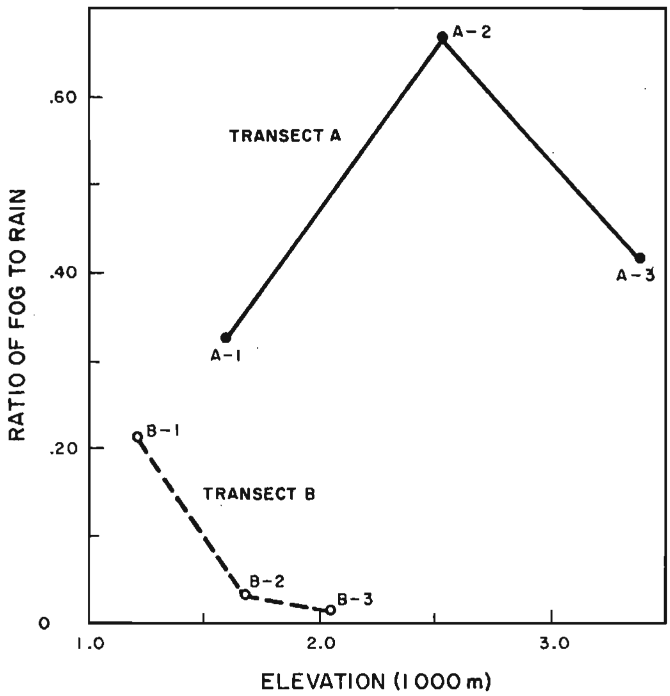


FIGURE 19. COMPARISON OF FOG:RAINFALL RATIOS FOR TRANSECT A AND B STATIONS, WINDWARD MAUNA LOA, HAWAI'I ISLAND, 1974-1975

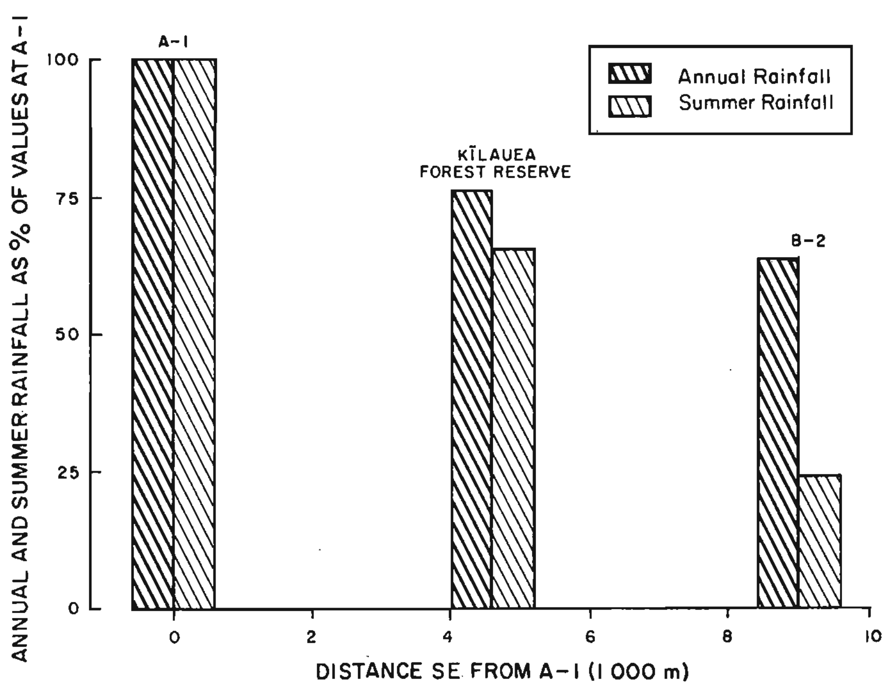


FIGURE 20. COMPARISON OF ANNUAL AND SUMMER RAINFALL ALONG THE 1 650-m CONTOUR FOR STATIONS A-1 AND B-2, AND KĪLAUEA FOREST RESERVE, HAWAI'I ISLAND

It is evident from this diagram that summer rainfall decreases to the southeast at a rate more than twice as fast as the decrease in annual rainfall. The sharp reduction in summer rainfall at Station B-2 can only be attributed to a decreased frequency of the summer orographic cloud in that area. Rainfall from general synoptic disturbances is largely absent during the summer months.

The steep decline in summer rainfall measured over 10 000 m along the contour probably reflects the influence of a relatively subtle topographic feature. Recent and prehistoric lava flows emanating from the northeast rift zone of Mauna Loa have built up a gently sloping, yet well-defined, ridge extending down the flank and lying roughly in the area between Transects A and B of Mauna Loa. With respect to the prevailing tradewind circulation, Station B-2 occupies a location distinctly to the lee of this ridge and does not possess a clear, continuous downslope view of the prevailing tradewind flow. This subtle ridge appears to effectively limit lateral expansion of the summer orographic cloud and its associated rainfall (Fig. 18). Fog would be even less likely to occur than rain leeward of the ridge formed by the northeast rift zone because the descent of the orographic cloud to ground level (forming what is here defined as mountain fog) is influenced even more by minor topographic barriers than by the production of orographic rain. This conclusion is justified because fog decreases even more sharply between A-1 and B-2 than the falloff in summer rain (Fig. 19).

In summary, the disparity between Transects A and B fog values results from a rather unique topographic situation which one would not expect to see replicated in more typically exposed locations on the windward slope. It would appear, then, that the characteristics of windward fog depicted in the Transect A data can be safely extrapolated to adjacent areas within the general areal extent of the windward orographic cloud, possibly including windward Mauna Kea as well.

DIURNAL VARIATION IN SUMMER FOG AND RAINFALL. The gross relationships between rainfall and fog have been discussed in preceding sections of this report. While covariation in monthly rain and fog data proved significant, a greater refinement of the relationship could be expected through the examination of continuous data for individual precipitation episodes. Short-term continuous monitoring of rain, fog, and wind parameters was

undertaken at Station B-1 during the spring and summer months of 1974 to investigate diurnal precipitation patterns and the fog-to-rainfall interaction within an hourly time frame. Data are analyzed for a total of 21 days with precipitation drawn from April, May, and June 1974. Daily precipitation hours are segregated into either fog or rainfall on the basis of average drop-size estimates. Drop sizes are derived from the fog-to-rainfall ratio by the method discussed on pages 7 to 12. Precipitation hours are classified as fog if the estimated drop diameter falls below 100 μ. Over the 21 days, there is a total of 176 precipitation hours, of which 75 are classified as fog and 101 as rainfall. The total rainfall for the period is 80.3 mm, with fog equal to 34.1 mm. Figure 21 depicts the pattern of rainfall and fog hours.

The diurnal frequency distribution of rainfall and fog hours shows general agreement, although the nighttime maximum for fog occurs several hours later than for rainfall. In reviewing the data for individual precipitation periods, evening light rainfall episodes are observed as sometimes degenerating into drizzle and fog later in the night. The general lag in fog frequency maximum is consistent with this observation.

Figure 22 illustrates that all of the rainfall and fog is associated with upslope tradewind flow and that there is no distinction between rainfall and fog episodes relative to prevailing wind direction.

Wind velocity data for the precipitation hours are also analyzed. No consistent pattern emerges, however, for relating differences in wind speed to the occurrence of fog or rain episodes.

The rainfall changes from a nighttime maximum along the coastal areas to a distinct afternoon maximum in the main fog belt on the upper slopes of the windward coast, and the expected diurnal pattern of fog catch must also change (Schroeder, Kilonsky, and Meisner 1977).

In conclusion, the diurnal data indicate no significant temporal separation of fog and rainfall episodes. Neither is there any distinction between rainfall or fog occurrence with respect to prevailing wind conditions. The occurrence of rainfall or fog in a given "orographic episode" is probably governed by relatively subtle differences in cloud water content, air parcel, and surface temperatures.

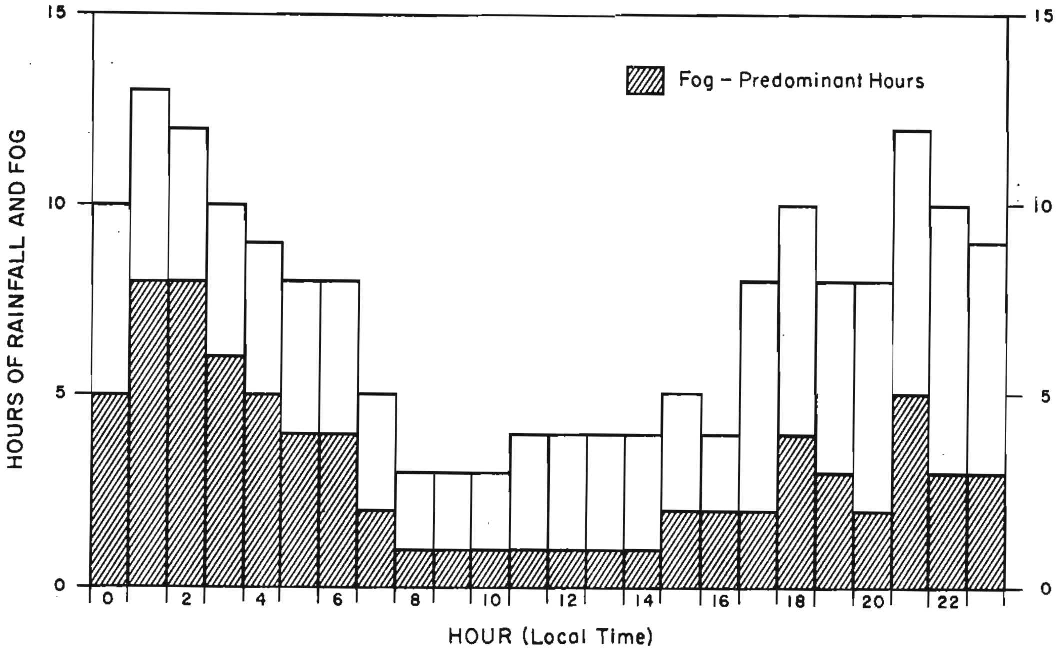


FIGURE 21. DIURNAL PATTERN OF RAINFALL AND FOG HOURS FOR 21 PRECIPITATION DAYS DURING SUMMER 1974, HAWAII NATIONAL PARK HEADQUARTERS (B-1) STATION, HAWAI'I ISLAND

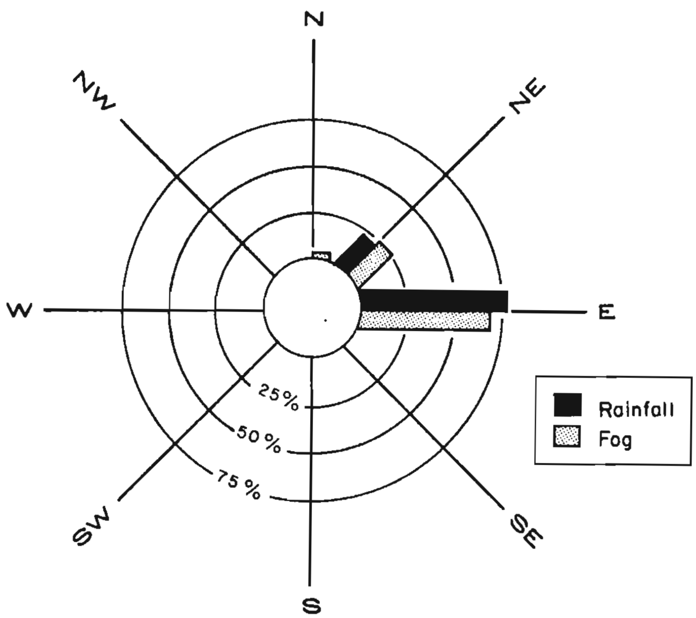


FIGURE 22. RAIN AND FOG FREQUENCY BY WIND DIRECTION CATEGORIES FOR 21 PRECIPITATION DAYS DURING SUMMER 1974, HAWAII NATIONAL PARK HEADQUARTERS (B-1), HAWAI'I ISLAND

Leeward Mauna Loa

ALTITUDINAL FOG GRADIENT. On leeward Mauna Loa, fog interception was monitored during 1974 to 1975 at a total of 12 stations located along three altitudinal transects (Fig. 5).

Transect C cumulative rainfall and fog totals for the 15-mo period, March 1974 through June 1975, are arrayed against station elevation in Figure 23. For the period involved, total rainfall was near the long-term normal, e.g., 80% of normal at the intermediate Station C-5.

The rainfall profile in Figure 23 is characterized by a steep initial decline, followed by a more gradual decrease at higher elevations. This pattern conforms with the general gradient in Kona rainfall (Taliaferro 1958). The drastic decrease in rainfall between 1 100 and 1 300 m results from the location of these stations near the upper margin of a relatively narrow summer convectional rainfall belt. This high rainfall belt is characterized by peak precipitation in the altitudinal zone between 600 to 800 m, with a very steep rainfall decline at elevations above and below this level (Fig. 18).

Fog interception values for the period show a consistent increase with elevation (above 1 300 m), both in absolute and relative terms. It will be observed that the increasing fog precipitation with elevation almost compensates for the decreased rainfall at higher stations. At Transect C-7 the combined rainfall and fog (1 320 mm) is almost identical to that recorded at C-4, at an elevation almost 900 m lower on the slope.

SEASONAL VARIATION IN FOG. The seasonality of fog occurrence in leeward Hawai'i is analyzed on the basis of monthly data for Transect D. This transect is located on the slopes of Hualālai, rather than on Mauna Loa; however, the orientation of Transect D stations with respect to local circulation is similar to the other leeward transects on Mauna Loa (Fig. 5). It is not possible to utilize Transect C data in the monthly analysis because, for the uppermost stations on this transect, gage readings were sometimes taken at 6- to 8-wk intervals.

The array of monthly Transect D rain and fog values for the period August 1974 through December 1975 is presented in Table 10. Over the entire sampling period, rainfall averaged 79, 95, and 83% of the long-term normal values for the respective Stations D-1, D-2, and D-3. However, note that in Table 10 there is substantial deviation from long-term normals for

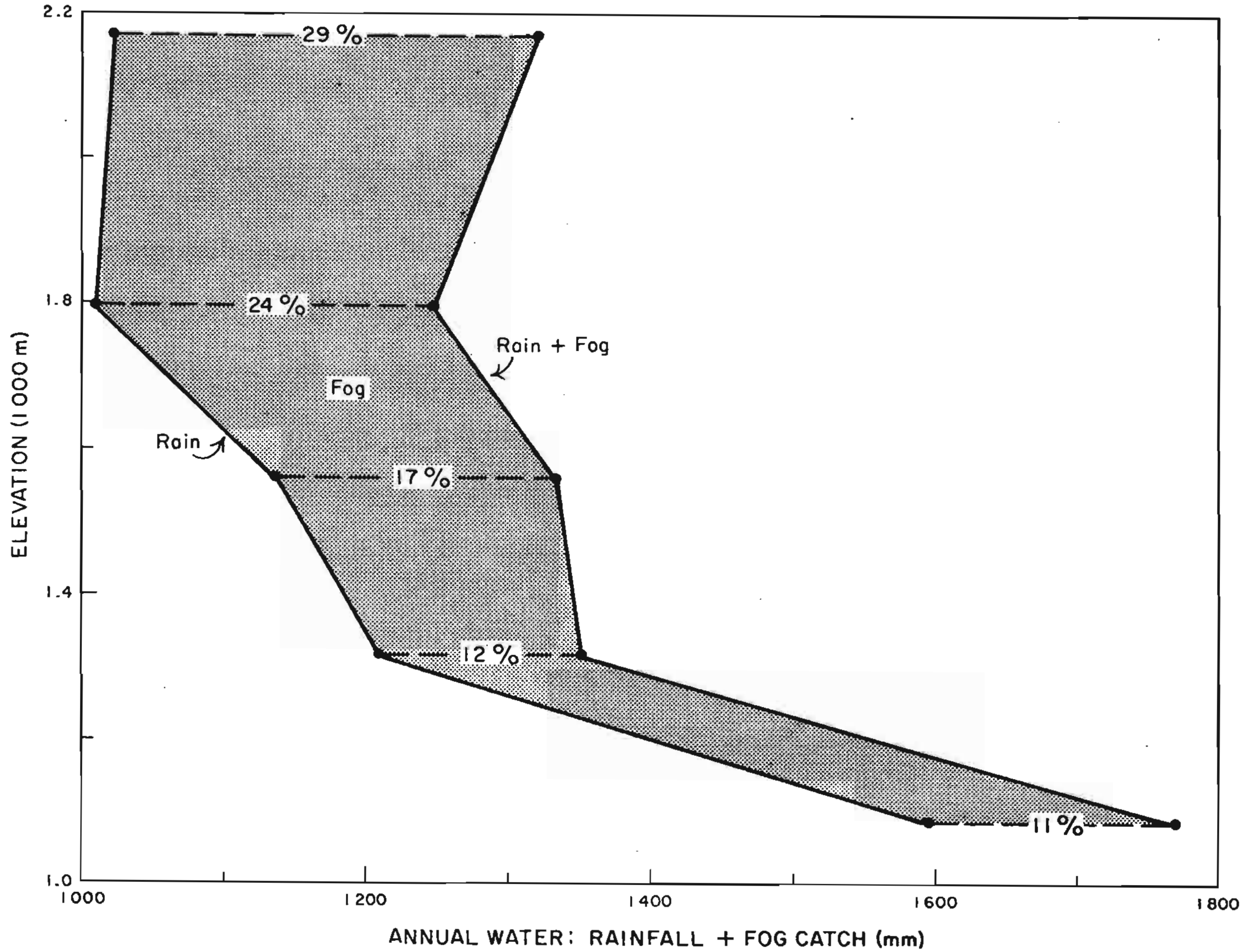


FIGURE 23. CUMULATIVE 1974-1975 RAINFALL AND FOG ON LEEWARD MAUNA LOA (KONA TRANSECT C), HAWAI'I ISLAND, MARCH 1974-JUNE 1975

TABLE 10. TRANSECT D MONTHLY RAINFALL AND FOG CATCHMENT, 1974-1975, HŌLUALOA, HONUA'ULA, HUALĀLAI, HAWAI'I ISLAND

	1974					1975												
	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Period
D-1 Hōlualoa (el. 981 m)																		
Rain (mm)	99.1	107.7	548.6	63.5	23.1	45.7	271.8	--	--	--	198.4	114.8	96.5	88.9	78.7	96.5	23.6	1857
Fog (mm)	14.3	14.4	16.3	5.1	2.0	2.1	1.6	--	-- no data	--	16.4	16.7	11.0	8.4	11.5	12.6	1.8	134
Fog:Rain Ratio	0.14	0.13	0.03	0.08	0.09	0.04	0.01	--	--	--	0.08	0.15	0.11	0.09	0.15	0.13	0.08	0.09
Rain, % Normal	50	50	333	54	33	34	260	--	--	--	82	56	49	41	48	82	33	80
D-2 Honua'ula (el. 1 905 m)																		
Rain (mm)	25.9	69.1	121.9	48.0	21.6	31.0	299.7	114.3	43.4	43.4	57.4	42.2	48.3	49.5	45.5	83.8	14.0	1192
Fog (mm)	12.4	15.8	23.9	10.4	6.9	5.2	45.7	16.2	28.1	28.1	28.4	16.2	16.3	4.1	10.3	22.6	4.4	304
Fog:Rain Ratio	0.48	0.23	0.19	0.22	0.33	0.17	0.15	0.14	0.65	0.65	0.49	0.36	0.34	0.08	0.23	0.27	0.31	0.29
Rain, % Normal	31	76	200	85	52	30	377	109	56	56	56	48	59	55	75	149	34	86
D-3 Hualālai (el. 2 496 m)																		
Rain (mm)	29.2	38.9	49.5	32.0	20.1	27.4	195.6	18.5	13.5	4.1	3.8	6.6	34.3	14.5	10.2	24.4	5.6	528
Fog (mm)	39.4	71.5	66.1	68.5	18.5	8.6	32.5	56.8	48.0	69.7	35.1	77.1	64.7	54.8	19.6	55.7	46.1	832
Fog:Rain Ratio	1.35	1.84	1.33	2.14	0.92	0.31	0.17	3.07	3.57	17.14	9.22	11.68	1.89	3.78	1.93	2.28	8.25	3.94
Rain, % Normal	73	74	164	126	103	49	430	32	35	7	9	16	85	28	34	96	29	77

the individual monthly values. The presence of large-scale and persistent cyclonic systems during February 1975 resulted in monthly rainfall ranging from 260 to 430% of normal at the three stations. The impact of these large-scale synoptic disturbances is also evident in the data for windward Mauna Loa stations (Table 3). On the leeward Transect D, the February rainfall of 195 mm at D-3 was nearly 40% of the total rainfall recorded during the 17-mo sampling period. By contrast, rainfall in the remaining months, with few exceptions, was well below normal at all three stations. In general, impact of winter cyclonic storms is also reflected in the winter-summer differences in the altitudinal rainfall gradient. Large-scale synoptic disturbances in winter tend to "overpower" the localized climatic controls exerted by the island, and the copious winter rainfall is often distributed independently of elevation. For February 1975, the maximum rainfall was at the intermediate level, D-2 (299.7 mm), rather than the expected lowest level, D-1 (with only 271.8 mm), while rainfall at the highest level, D-3 (195.6 mm), was 72% rather than the usual 44% value at D-1. In contrast to this somewhat random winter pattern, an examination of the summer data, e.g., June to September 1975, reveals a consistently steep precipitation decay with elevation, reflecting precipitation control by the local land-sea breeze regime.

The seasonality of fog in leeward locations is depicted by the array of monthly values for the fog-to-rain ratio plotted in Figure 24. The data reveal a distinctive summer maximum in relative fog for all three stations, although this maximum is most clearly depicted in the D-2 values.

The extraordinarily high fog-to-rain values typical of D-3, particularly for the months May through June 1975, must be carefully interpreted in view of two extenuating factors:

1. D-3, unlike all other sampling stations, is located at a mountain summit site (Hualālai) and, thus, is unique in having omnidirectional exposure to upslope clouds. Higher wind speeds usually associated with summit locations may also be a factor in the increased fog interception.
2. Months with extreme fog-to-rain values result not so much from dramatic increases in absolute fog but, rather, because the ratios are exaggerated due to subnormal rainfall (Table 10). As an example, during May 1975, intercepted fog was over 17 times greater than rainfall; however, rainfall was virtually nil,

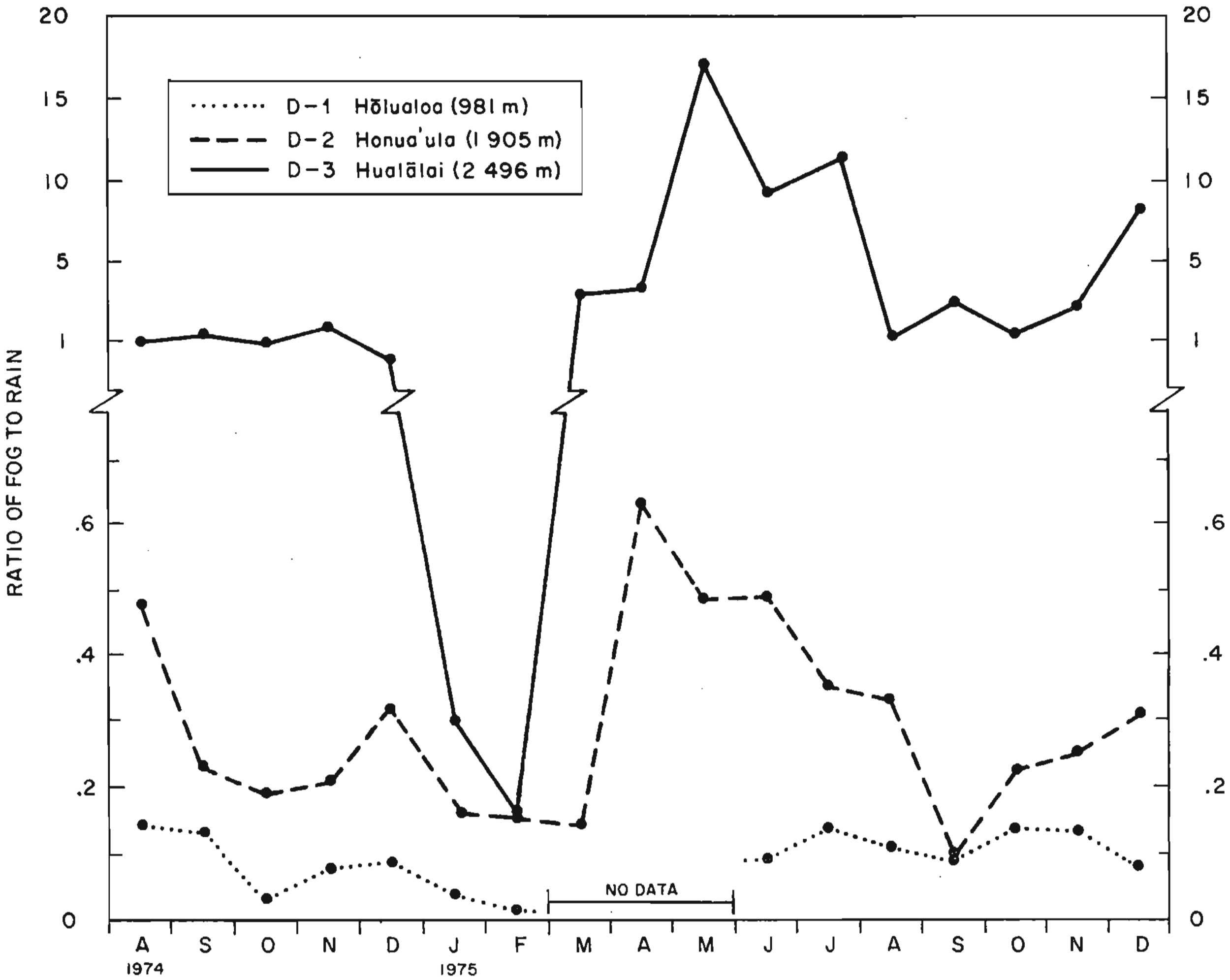


FIGURE 24. SEASONAL VARIATION IN MONTHLY FOG:RAINFALL RATIOS FOR KONA TRANSECT D, HAWAI'I ISLAND, 1974-1975

equaling only 7% of the monthly normal.

The August (1975) data are perhaps representative of the "typical" summer situation in the summit area. In this month, with rainfall near normal (85%), fog interception is a little less than twice the recorded rainfall. The very low fog-to-rain ratios recorded at D-3 for the months of January and February correspond to the extreme positive rainfall departures for these months with severe cyclonic storms.

It should be noted that the initial decision to limit transect and sampling stations to sites with long-term rainfall records proved worthwhile, for, whereas it limited the ideal scatter of sampling sites on the mountain slopes, the results derived are more meaningful for interpretation of extreme values.

If the data from D-1 (where fog is minimal) and D-3 (with its unique site properties) are disregarded, then the monthly values for D-2 may reasonably be assumed as representative of seasonal variations in mountain fog for leeward (Kona) areas.

RELATIONSHIP BETWEEN RAINFALL AND FOG. In an analysis similar to that undertaken for the windward data, as described earlier, the monthly summer and winter rain and fog values for Station D-2 are fitted by linear regression (February 1975 data excluded). The scattergram and resultant linear regression equations are presented in Figure 25.

For the summer and winter periods, the correlation coefficients are respectively 0.507 and 0.903. The relatively poor correlation for the summer data may in part reflect the low number (8) of cases that are analyzed. It will also be observed from the data in Table 10 that, as was demonstrated for the windward data, rainfall departure from normal exhibits some association with the fog-to-rain ratio. However, due to inadequate sample size, no analysis comparable to that presented for Transect A (Fig. 14) was undertaken.

CROSS-SLOPE VARIATION IN FOG. As opposed to upper level windward locations, the leeward slope of Mauna Loa (and Hualālai) in the Kona area is characterized by elevation contours which tend to be more linear and oriented parallel to the coast. This simplified topographic alignment serves to minimize cross-slope variation in rainfall precipitation. It will be noted from Figure 18 that isohyets are more nearly parallel to the elevation contours in the Kona area as compared to windward locations. In

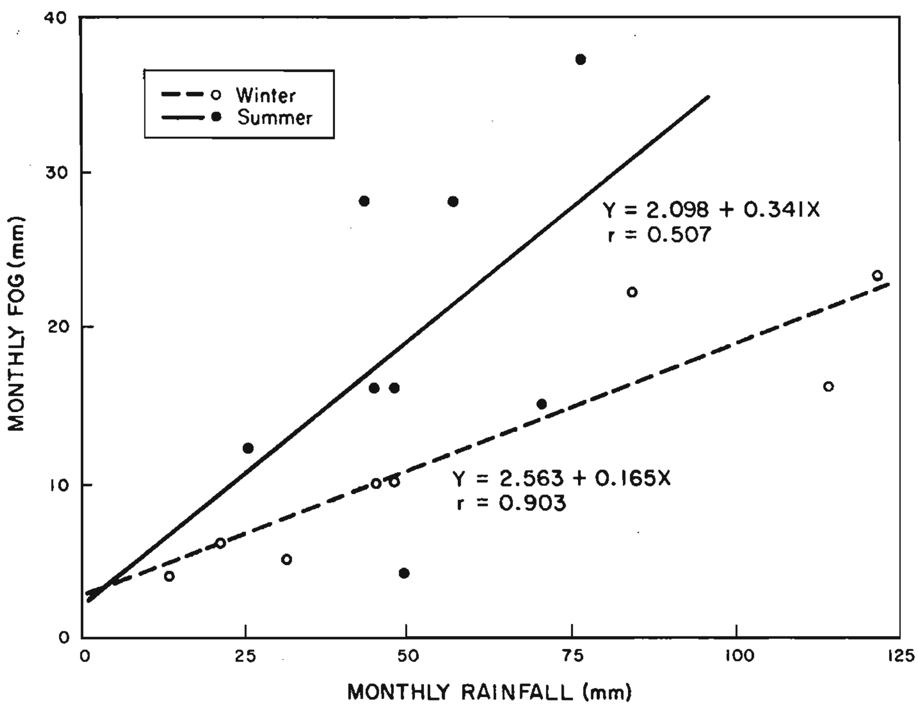


FIGURE 25. RELATIONSHIP BETWEEN RAINFALL AND FOG AT HONUA'ULA STATION D-2, HAWAI'I ISLAND, 1974-1975

view of this, it was hypothesized that the relative fog contribution in mountainous areas throughout Kona should likewise show little cross-slope variation. The total sample period fog-to-rain ratios for all Transect C, D, and E stations were plotted together against station elevation and fitted by linear regression (Fig. 26). The regression coefficient of 0.957 is extremely strong considering that the data include stations as much as 35 000 m apart, e.g., D-2 and E-1. The results clearly indicate that there is very little cross-slope fog variation in the area bounded by Transects D and E. This simple altitudinal model appears adequate to describe rain and fog relationships for the Kona district.

DIURNAL VARIATION IN SUMMER FOG AND RAINFALL. Short-term continuous measurement of precipitation and wind parameters was conducted at Station C-5 (el. 1 560 m) during 1974 to describe diurnal patterns of summer rainfall and fog occurrence on the leeward mountain slope of Mauna Loa. Again, hourly precipitation values were partitioned into either rain or fog episodes on the basis of estimated drop size. For a total of 20 days with precipitation, monitored during May, June, and August 1974, there were 118 precipitation hours, of which 62 hr were classed as rain, i.e., estimated drop diameter greater than 100 μ, and 56 hr as fog. The total rainfall for

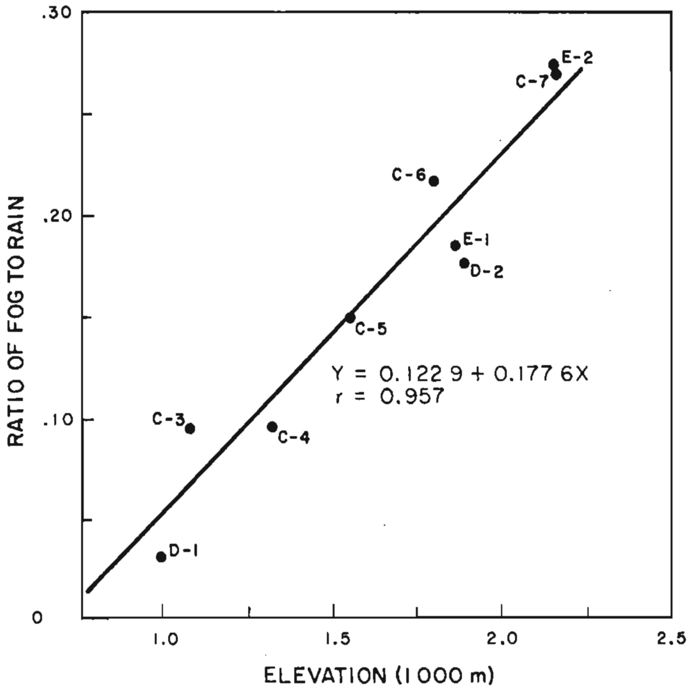


FIGURE 26. RELATIONSHIP BETWEEN STATION ELEVATION AND THE FOG:RAIN RATIO FOR COMBINED KONA TRANSECTS, HAWAI'I ISLAND

this period was 57.40 mm, and fog 12.16 mm. The diurnal distribution of rainfall and fog hours is presented in Figure 27. The frequency curves for both forms of precipitation are virtually identical. Both rainfall and fog were limited exclusively to the afternoon and evening hours, exhibiting a maximum frequency in the period 1500 to 1800 hr.

Leeward Mauna Loa is characterized by a well-defined local, land-sea breeze circulation, merging with a mountain-valley wind on the upper slopes of the volcano. The diurnal wind reversal is a key component in this daytime cloudiness and rainfall maximum (Schroeder, Kilonsky, and Meisner 1974).

An analysis of prevailing wind direction during precipitation episodes at C-5 (Fig. 28) indicated that both rainfall and fog are almost exclusively associated with the upslope (daytime) wind. This wind reached maximum strength in the afternoon and was replaced by a shallow downslope wind at some time after 1800 hr. During the 20 precipitation days monitored, the evening downslope wind never failed to materialize, although the actual time of reversal varied from 1700 to 2400 hr. In all but two cases the afternoon precipitation episodes terminated within the hour preceding the

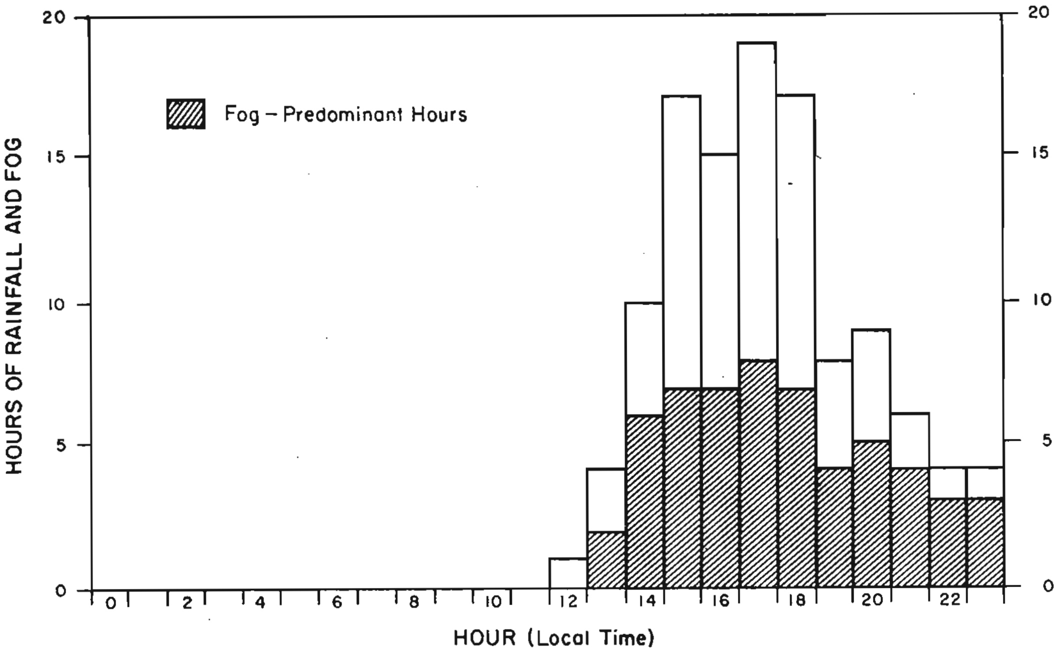


FIGURE 27. DIURNAL PATTERN OF RAINFALL AND FOG HOURS FOR 20 PRECIPITATION DAYS DURING SUMMER 1974, PAPALOA KONA (C-5), HAWAI'I ISLAND

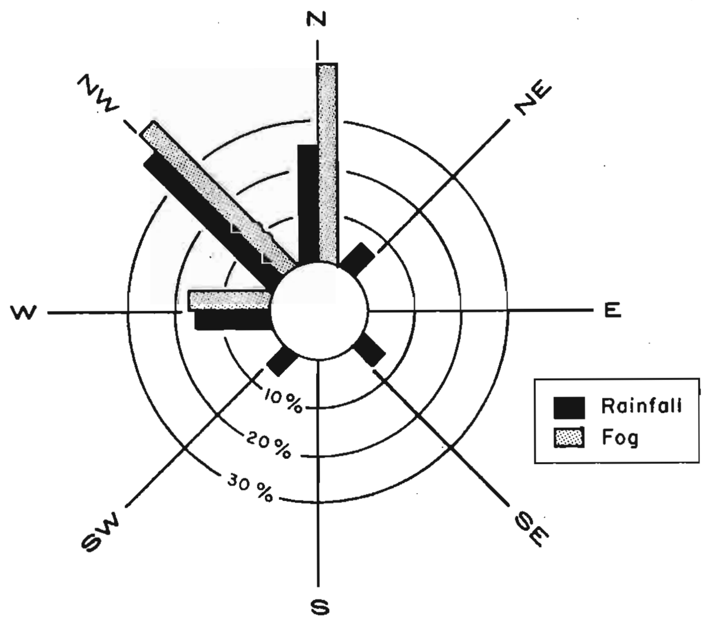


FIGURE 28. RAINFALL AND FOG FREQUENCY BY WIND DIRECTION CATEGORIES FOR 20 PRECIPITATION DAYS DURING SUMMER 1974, PAPALOA KONA (C-5), HAWAI'I ISLAND

evening wind reversal. The exceptions (frequency bars from the SE and SW in Fig. 28) were two relatively heavy rain episodes that continued for a short time after the wind reversal. These situations doubtless represent a temporary lingering of an upslope orographic-convectional system aloft, with rain falling through the shallow downslope flow. The lack of any distinctive temporal separation between rainfall and fog frequency, and the congruence with respect to prevailing wind direction, confirm that the two precipitation forms simply represent different "magnitudes" of a single condensation process.

Comparison of Windward and Leeward Fog

A review of the fog interception results discussed in this chapter points to the potentially significant role of fog moisture in the water balance of mountain ecosystems on both windward and leeward Mauna Loa. The consistently higher fog values on the windward slope are evident in a comparison of the altitudinal fog profiles (Figs. 6 and 23).

As shown in Figures 22 and 28, fog is almost exclusively associated with upslope winds. The lower Kona fog values are to be expected with the sheltered leeward location, where upslope air flow is purely dependent on localized differential heating and lacks any enhancement from a parallel tradewind field (as prevails windward). The effect of aspect is evident in the following quantitative comparisons: windward Station A-1 (el. 1 530 m), for the period 1974 to 1975, recorded annual fog-to-rain ratios of 0.28 and 0.37; in Kona at a similar elevation (1 550 m), Station C-5 yielded a ratio of only 0.17.

Ekern (1964) reported a comparatively high annual fog-to-rain ratio (0.65) at a much lower elevation (840 m) on Lana'i Island; however, the Lana'i site, occupying a summit-ridge location, is subject to substantial fog enhancement. A similar situation was clearly evident in the Hualālai summit data (Sta. D-3) presented in Figure 24. Extreme fog concentrations at ridge and summit locations, while interesting (and potentially important as sites for the installation of large-scale mechanical catchment systems), are, by virtue of limited areal extent, insignificant in a general spatial analysis of fog contribution. By contrast, the altitudinal and cross-slope fog relationships derived in the present study, though less dramatic in absolute terms, are ultimately more important in facilitating the spatial

integration of the fog contribution for extensive mountain watershed areas.

The summertime maximum for relative fog, exhibited in both the windward and leeward fog data, is in agreement with the results of the Lana'i study and also the data collected at the Hawaii Volcanoes National Park by Smathers and Mueller-Dombois (1972). Based on relationships between fog and tradewind inversion, the summer maximum in the fog-to-rain ratio appears related to general periods of increased atmospheric stability (Figs. 16 and 17).

Only one previous study (Vogelman 1973) on mountain-fog gradients lends itself to direct quantitative comparison with the Mauna Loa results. That investigation was undertaken on the windward slopes of the Sierra Madre Oriental in central Mexico. The general climatic conditions there are similar to Hawai'i, i.e., prevailing onshore tradewinds with precipitation predominately of orographic origin.

Vogelman found that fog was a "significant ecological factor" at elevations between 1 300 and 2 400 m, an altitudinal range comparable to the fog belt on windward Mauna Loa. Unfortunately, Vogelman failed to render his data in a "unit vertical catch" format; however, with specifications on the dimensions of his fog interceptor, an approximate transformation of his data (to Mauna Loa compatible form) was possible. By way of comparison, Vogelman's Las Vegas station, located at an elevation of 2 410 m, which most closely corresponds to the elevation of Station A-2 on Mauna Loa, recorded annual rainfall of 1 620 mm for the year 1969, while a companion fog gage collected 2 095 mm, or an excess of 475 mm. This value can be reduced to unit vertical catchment by dividing by the ratio of the fog interceptor screen area to the cross-sectional area of the rain gage. Based on the gage specifications given, the interception screen area was approximately 480 cm^2, or 6.79 times the cross-sectional area of the rain gage. Dividing the fog value (475 mm) by 6.79 yields a unit vertical area fog catchment of 70.0 mm and a fog-to-rainfall ratio (70.0/1620) of 0.043.[1] This ratio is quite low when compared with the values of 0.70 and 0.65 recorded respectively for 1974 and 1975 at Station A-2 on Mauna Loa. Vogelman's fog interceptors employed aluminum mesh window screen (288 mesh/in.) as opposed to the louvered screen utilized in the Mauna Loa study. As discussed elsewhere in

[1]This value is representative of those Vogelman recorded for stations within the fog belt, such as *Altotonga*, 0.033; *Jalapa*, 0.046; and *Totutla*, 0.046.

this paper, Ekern (1964) has demonstrated that wire mesh (because of poor drainage) is a substantially less efficient fog interceptor than that of the louvered screen. Examination of the two localities indicates a similarity in the general dimensions of the fog belt, but significant divergence in actual fog values.

A NOTE ON THE FEASIBILITY OF LARGE-SCALE MECHANICAL FOG CATCHMENT

The present study uses louvered aluminum screen (Kaiser Shadescreen) as the standard fog interception material. Bruce (1966), however, has shown that this material, when installed in large panels, is easily ripped by the wind. At a price of \$4.00 to \$5.00/m^2 (plus an estimated \$2.00/m^2 to provide the rigid vertical support system), it is relatively expensive.

A suitable interception material must combine the qualities of low price, durability, ease of installation, and efficient fog collection. "Sugi" net, a small mesh (9.0-mm^2) monofilament fishnet, offers one prospect in fulfilling these criteria. The net filament is 0.3 mm in diameter, with 1-mm diameter knots tied at 9-mm intervals. A square meter of net has an actual surface area for interception of 1 045 cm^2 or about 10% of the total area. The cost of the "Sugi" net is approximately \$1.70/m^2. Fog catchment by "Sugi" net (both single and double layers) in "window frame" fog gage (Plate 1) at Stations A-1 and E-2 over a 4-mo period in 1975 averages 15.9% of that in a standard fog gage for single layer "Sugi" net and 30.7% for double layer. The lower collection efficiencies are to be expected since the single layer "Sugi" net is almost 90% open space.

Since the single layer "Sugi" net collects only about one-sixth the fog of a standard fog gage, it follows that for the net to recover water at the same unit area rate as a horizontal rain catchment, then the fog-to-rainfall ratio for the site must exceed 6. However, a surface rain catchment of sheet metal, concrete, or asphalt may cost 5 to 10 times more per m^2 (\$10.00 to \$15.00/m^2, installed in a mountain area) than the "Sugi" net. The use of the "Sugi" net can be economically justified in areas with a fog-to-rain ratio as low as 1.0 to 1.5 for substantial parts of the year.

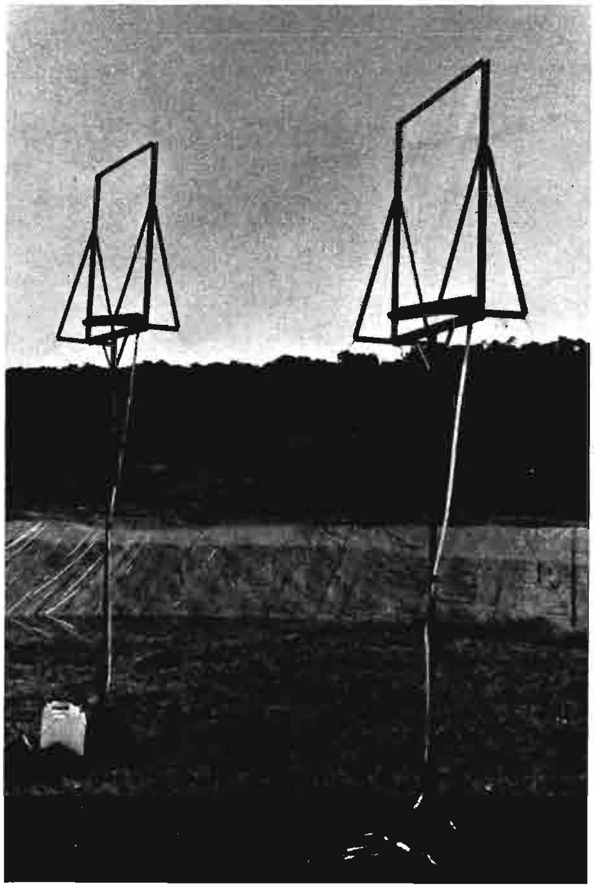


PLATE 1. "WINDOW-FRAME" FOG GAGES INSTALLED AT STATION E-2 (2 164-m el.) ON LEEWARD MAUNA LOA, HAWAI'I ISLAND

In 1973 the McCandless Ranch installed a 123-m^2 "Sugi" net fog interceptor over a rain-catchment reservoir, at an elevation of 2 164 m (Station E-2) on leeward Mauna Loa (Plates 2 and 3). Subsequent evaluation of the site, however, indicates negligible fog catchment.

Annual rainfall at Station E-2 is approximately 800 mm; and based on louvered-screen, fog-gage data, the annual fog to rainfall catchment ratio is 0.3, or 240 mm of annual fog. The "Sugi" net will intercept 15.9% of this value or 38.15 mm/yr. An area of 123 m^2 of "Sugi" net would have an annual catchment of only 0.5 m^3.

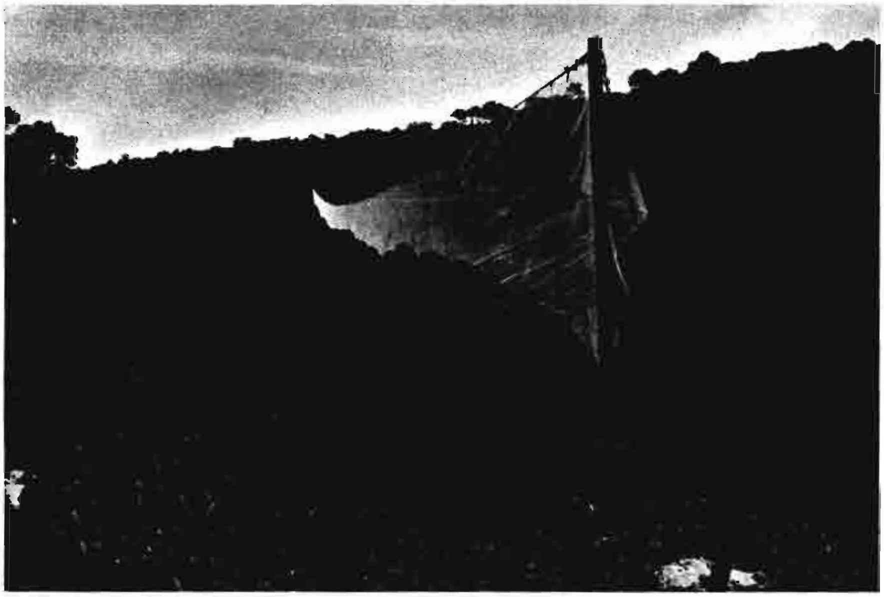


PLATE 2. "SUGI" NET FOG CATCHMENT AT STATION E-2 (2 164-m el.) ON LEEWARD MAUNA LOA, HAWAI'I ISLAND

PLATE 3. FOG NET OVER BUTYL RUBBER RAIN CATCHMENT RESERVOIR, STATION E-2, LEEWARD MAUNA LOA, HAWAI'I ISLAND

A very tentative estimate of the absolute fog water contribution on windward Mauna Loa may be derived by integrating the fog and rainfall contribution across slope and at different elevations in the windward aspect. Davis and Yamanaga (1968) investigated the hydrology of windward Mauna Loa (an area incorporating Transect A in the present study). They found that rainfall over the $2.46 \times 10^9 m^2$ Hilo-Puna watershed averaged 3.05 m/yr, or 2.379×10^2 m^3/s. If the mountain forests of Mauna Loa can be assumed to exhibit a similar ratio of fog-to-rain collection as recorded in the louvered screen gages, then total fog over the watershed may be approximated. If it is further assumed that fog collection is negligible below the 900-m elevation and also above 2 000 m (the upper limits of forest occurrence), then an average fog-to-rain ratio of 0.31 for the 900- to 2 000-m zone may be calculated by extrapolation and integration of the data presented in Figure 6. Average rainfall within this altitudinal zone is 3 050 mm/yr (identical to the average rainfall over the entire watershed), and thus the annual fog may be calculated as $0.31 \times 3.05 = 0.93$ m/yr. The altitudinal zone between 900 to 2 000 m constitutes 33% or 8.18×10^8 m^2 of the total watershed area. At 0.93 m/yr, total fog water production within this zone would be 24.1 m^3/s. This 24.1 m^3/s is equal to 10.4% of the rainfall over the entire watershed. Although it represents a rather modest contribution for the watershed as a whole, within the mountain zone a fog contribution of 930 mm/yr could probably offset most or all of the annual evapotranspiration demand (estimated at between 800-1 000 mm/yr).

SUMMARY AND CONCLUSIONS

This study investigates spatial and climatological aspects of the mountain fog regime on Mauna Loa, Hawai'i Island. A louvered-screen fog gage was developed for standardized measurement of fog interception together with a methodological technique for isolating the fog component of precipitation episodes on the basis of fog and rain-gage geometry and the physical relationship between droplet size, inclination angle, and wind speed. In addition, methods for relating mechanical fog interception data to actual forest fog drip are investigated. On Hualālai fog drip, as reflected in increased undercanopy soil moisture, can be reasonably predicted from mechanical interception data.

The spatial distribution of mountain fog on Mauna Loa is determined from a network of fog gages installed along altitudinal transects at windward and leeward locations. On windward Mauna Loa a well-defined fog belt occurs at elevations between 1 500 to 3 000 m. At about 2 500 m, the fog-to-rain ratio (on an annual basis) equals 0.65 to 0.70.

The seasonal distribution of mountain fog on windward Mauna Loa exhibited a strong summer maximum at elevations below 2 500 m and a weak winter maximum on the higher slopes (3 400 m).

This reversal in seasonal fog occurrence is attributed to the influence of the summer tradewind inversion which precludes cloud penetration to the higher mountain slopes. The summer fog maximum at lower elevations is associated with increased orographic condensation which results from the combined effects of a seasonally stronger upslope sea/mountain breeze which intensifies tradewind field.

Vertical development of the summer orographic cloud is hampered, however, by a seasonally stronger, upper-air inversion which produces a "fog-forming, stratus-cloud wedge" on the upper slopes of the mountain.

A summer fog maximum is also experienced on the leeward slopes of Mauna Loa in association with sea breeze/mountain upslope circulation of the Kona type.

Simple and multiple regression analyses of fog, rain, topographic and upper-air parameters have demonstrated that mountain fog (daily, monthly or annual) can be reliably predicted for different slope locations. In the climatologically less complex leeward Mauna Loa environment, 91.6% of the annual variation in fog can be explained by elevation alone (Fig. 26).

On the more complex windward aspect, rainfall and a variety of upper-air parameters combined to explain 60 to 88% of the variation in daily and seasonal fog interception (Figs. 10, 11, and 12; Tables 7 and 8).

This study demonstrates the significant contribution of mountain fog to the water balance of mountain areas on Hawai'i Island. Through a quantitative characterization of the mountain fog regime, the study also provides a data base for investigating the economic feasibility of large-scale fog catchment systems and the contribution of fog in mountain-forest ecology.

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