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METHODOLOGICAL APPROACHES IN HAWAIIAN FOG RESEARCH  
James H. McKnight, et al  
Hawaii University

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**METHODOLOGICAL APPROACHES  
IN HAWAIIAN FOG RESEARCH**

**James H. McKnight**

**James O. Juvik**

**MARCH 1975**

*Water Resources Research Center*

University of Hawaii, Honolulu, Hawaii

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Recent studies have demonstrated the important moisture contribution from fog precipitation in mountain areas on the island of Hawaii. ~~The present study investigates~~ research methodologies useful in the study of Hawaiian upslope fog, including: (1) development of an improved fog gage; (2) development of indirect approximation methods for estimating average droplet sizes during precipitation episodes and separating fog and rainfall components; (3) establishment of an extensive fog sampling network on the island of Hawaii employing continuous recording equipment, for both rain, fog, and wind; (4) development of an original computer program for detailed temporal and spatial analysis of rain, fog, and wind parameters.

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METHODOLOGICAL APPROACHES IN HAWAIIAN FOG RESEARCH

by

James H. McKnight  
James O. Juvik

Technical Report No. 85

March 1975

Project Completion Report  
for

FOG PRECIPITATION ALONG TOPO-CLIMATIC GRADIENTS  
ON THE ISLAND OF HAWAII

OWRT Project No. A-041-HI, Grant Agreement No. 14-31-0001-4011  
Principal Investigator: James O. Juvik  
Project Period: July 1, 1972 to June 30, 1975

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## ABSTRACT

*Recent studies have demonstrated the important moisture contribution from fog precipitation in mountain areas on the island of Hawaii. The present study investigates research methodologies useful in the study of Hawaiian upslope fog, including: (1) development of an improved fog gage; (2) development of indirect approximation methods for estimating average droplet sizes during precipitation episodes and separating fog and rainfall components; (3) establishment of an extensive fog sampling network on the island of Hawaii employing continuous recording equipment, for both rain, fog, and wind; (4) development of an original computer program for detailed temporal and spatial analysis of rain, fog, and wind parameters.*

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catchment area). The interaction of rain and fog in the louvered screen gage is discussed in greater detail in a following section.

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## INTRODUCTION

The objective of this paper is to assess a variety of methodological approaches for investigating the role and contribution of fog moisture in the water balance of mountain forest ecosystems on the island of Hawaii. Recent studies have demonstrated the important contribution of intercepted fog moisture on windward Mauna Loa; in the present study the research methodology employed in a more sophisticated analysis of fog is described and evaluated. The major goals in this study were to:

1. Test methods for droplet size determination in Hawaiian upslope fog
2. Develop a mechanical fog interceptor with geometrical properties that enable the clear separation of rain and fog components
3. Develop an accurate definition of a fog episode by separating fog from any nonvertical rainfall component, through an analysis of the physical relationships between rain inclination angle, wind speed, and droplet size
4. Compare the collection efficiency of the newly designed fog interceptor with that of the standard Grunow-type fog gage used in a number of previous studies
5. Devise an adequate sampling network, employing a combination of both automatic and manual equipment for evaluating the role of fog in both leeward and windward areas
6. Develop a computer program for reducing rain, fog, and wind data and for graphic display and statistical manipulation.

## LITERATURE REVIEW

Fog has been variously defined in terms of visibility, droplet size, or formational characteristics. For the purposes of this discussion, we shall simply define fog as a cloud at ground level, with droplet sizes below 100 microns predominating.

There are basically two types of fogs: radiation and advection. Radiation fog is formed by radiational cooling to dew point of shallow layers of quiet humid air overlying a chilled surface. Advection fog is formed when moist air moves across a cold surface. Upslope fog, a type of advection fog, occurs in the Hawaiian Islands when warm tropical air ascends mountain

slopes and cools to the saturation point at higher elevations.

Droplet size is an important factor in the "productivity", (i.e., water yield) of fog, and this variable is dependent largely on characteristics of the originating air mass. Fog that develops in continental source regions tends to have smaller droplets, higher concentrations, and a narrow size spectrum, while those originating in marine air generally have larger droplets and a wider size spectrum. Factors such as availability of moisture, type of cloud, availability and activity of condensation nuclei, age of the cloud, and the turbulent air motions all play a role in determining the growth of cloud droplets.

Nagel (1956) and List (1971) established the following arbitrary classes for distinguishing rain and fog from drizzle:

TABLE 1. ARBITRARY SIZE RANGE CLASSES FOR DISTINGUISHING RAIN AND FOG FROM DRIZZLE

CATEGORY	SIZE RANGE (NAGEL)	SIZE RANGE (LIST)
RAIN	200-600 microns	400-5000 microns
DRIZZLE	100-200 "	100-400 "
MIST	--	50-100 "
FOG	3-100 "	5-50 "
HAZE	0-3 "	--

Grunow (1960b), in his investigations into droplet size, found that fog formed in cold polar air is inefficient in producing large droplets, (diameters average 2 to 15 microns). In marine warm air masses, the cloud droplet spectrum was characterized by a broader range of 4 to 25 microns diameter, with a maximum frequency between 8 to 14 microns. Grunow found that the most productive fogs (2-3 mm/hr) occurred in nonraining cloud decks formed in degenerating marine air masses.

The effect of fog on vegetation was also investigated by Grunow (1960a), who found that minute precipitation played an important role as a water source for vegetation. The device which he used, the "Hohenpeissenberg Device", measures precipitation below the particle size which is needed to wet the standard rain gage. It was found in this study that nearly half of all rainfall fell into the category of minute precipitation.

Squires and Warner's (1957) study of the structure of orographic clouds on the slopes of Mauna Loa offers a partial explanation for the frequency of fog in the mountain areas of Hawaii. The average depth of orographic clouds

decreases from about 1200 m at sea level to a depth of 600 m at inland elevations of 1800 m. There is a somewhat sharp transformation from a cumuli-form structure near the ocean to a stratiform structure on the upper slopes. The general structure and shallow cloud depth would necessarily limit the growth of water droplets. The cloud droplet spectra obtained for low lying orographic clouds by Squires and Warner (1957) show a large quantity of droplets in the 12 to 18 micron range which Grunow (1960b, p. 115) considered optimum for interception by wire screens and trees in the forests of the windward Alps.

Nagel (1956) measured fog precipitation for a one-year period on Table Mountain, South Africa, using two rain gages, one equipped with a "fog catcher" made of wire mesh screen mounted on a standard 8-in. rain gage. Several problems were encountered, one being the air turbulence caused by the microtopography of the terrain, which made it difficult to obtain representative samples. However, Nagel pointed out that undisturbed airflow would also be difficult to measure because in an airstream with an upward directed component raindrops may move horizontally or upward. The fog precipitation for the one-year period was found to be 3299 mm, as compared with only 1940 mm, for rainfall.

On Lanaihale, on the island of Lanai, Hawaii, Ekern (1964) investigated the comparative efficiency of various fog collecting materials. He first constructed a harp patterned of vertical copper wires .01-in. diameter spaced .25 in. apart in a 37 x 37.5-in. frame. The harp was four feet off the ground, exposed adjacent to a tree, and kept oriented to the wind by use of a vane. The water collected was recorded in a standard 8-in. rain gage. Over a three year period, more than 1964 in. of water were collected by the harp while the standard rain gage caught only 104 in. (Ekern 1964, p. 420). After correction of the fog data to the unit vertical area of the rain gage, the fog interception was found to be 71 in., equal to 2/3 of the rainfall. Other materials were also tested for their interception efficiency. Air conditioning filters were found to be unsatisfactory; saran window screens retained water in the mesh and became impermeable to the wind. Vertical, louvered aluminum shade screens were found to be even more satisfactory than the harp, producing (per unit vertical area) 3.96 in. of water while the harp yielded 3.53 in., and the standard rain gage .99 in.

Fog and low lying clouds were investigated by Vogelmann et al. (1968),

on the slopes of the Green Mountains in Vermont. Three sampling sites were established at 540 m, 840 m, and 1080 m. Paired rain gages were used at each elevation, one unmodified and one with a double coil of aluminum wire screen set inside the gage and extending 16 cm above the top. Both of these gages were mounted on 6-ft wooden posts and set in the ground 5 feet apart in the center of clearings. Each week between 3 July 1967 and 27 August 1967 the water content was measured in millimeters. At 840 m, the screened rain gage gathered 5.0% more water than the unscreened rain gage while at 1080 m, the screened rain gage collected 66.8% more water than the unscreened gage.

Fog along an altitudinal gradient in the cloud forests of eastern Mexico was also investigated by Vogelmann (1973). Fog interceptors were set up at various elevations ranging from 16 to 2425 meters. The gages were constructed from 1-liter oil cans. Some of the gages were fitted with a cylinder of aluminum window screen. In all 12 different stations were set up: 3 on the dry coastal plain, 7 in and near the rain forest, and 2 on the dry plateau above the cloud forest. During the dry season, fog interceptors produced 85.1% of rainfall at 1330 m and 102.9% of rainfall at 1898 m. However, Vogelmann failed to reduce his data to unit vertical area equivalents, and percentage values reported are difficult to interpret.

Burton (1971) noted the capabilities of the giant redwood trees to gather water through interception of fog and low clouds and by absorption of this fog through the needles of the tree.

Juvik and Perreira (1974) in the pilot phase of an ongoing research program (of which this study is a part), set up fog interceptors at 4 different elevations on windward Mauna Loa: at 610 m, 1580 m, 2530 m, and 3415 m. These fog interceptors were constructed of aluminum louvered shade screens and were matched with corresponding 8-in. (20.32 cm) standard rain gages. They found that fog played an extremely important role, and that its relative contribution increased with elevation. At 2500 m, the fog intercepted (per unit vertical area) over a 7-month period equaled 65% of the direct rainfall. It was shown that with a simple set of regression equations one could predict fog interception as a function of rainfall and elevation. Juvik and Perreira also found that during summer drought periods the relative contribution of fog increased dramatically.

## DROPLET SIZES

Droplet size is an extremely important parameter in any consideration of fog interception by either natural vegetation or artificial screens. The efficiency of fog interception is dependent on the interrelation of droplet size and the nature of the intercepting surface. As noted earlier, in Hawaii when ascending air is compressed between the rising mountain and the trade wind inversion, the cloud is transformed from cumuliform (with good vertical mixing) to stratiform, thinly layered with poor vertical mixing, and correspondingly smaller droplet sizes. Specific droplet information is particularly important in any consideration of large scale artificial screen catchment, because the collection efficiency of many materials may change under different droplet sizes.

Grunow (1960b) investigating fog droplet sizes in the Alps found that the air mass source region largely determined the nature of the droplet spectrum (Fig. 1). Polar continental air masses generally had much smaller droplet sizes than tropical maritime air.

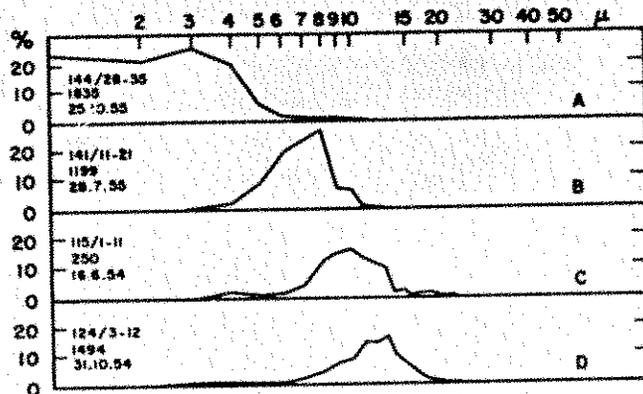
Squires (1958) undertook airborne transects in the sampling of the cloud droplet spectrum on windward Mauna Loa. Figure 2 illustrates his findings of droplet sizes in orographic and stratus clouds. The decrease in droplet size for stratus is evident.

In the present study an analysis of ground level fog-cloud droplet size was undertaken at two locations on windward Mauna Loa: Hawaii Volcanoes National Park Headquarters (Sta. B-1), el. 1170 m, and Kulani Honor Camp (Sta. A-1), el. 1580 m (Fig. 3). The magnesium oxide method of drop size determination was utilized (May 1950). Microscope slides are exposed to burning magnesium and coated with a thin oxide layer. The slide is then exposed to fog for a specified period of time. Water droplets leave an impact crater in the magnesium oxide directly proportional to the actual droplet diameter. The impact crater diameters are then measured under a microscope and multiplied by a correction factor (0.75) to determine the droplet size (May 1950). Figure 4 presents a microphotograph of an exposed magnesium oxide coated slide. Typical fog droplet impact craters are shown in size relationships to a 1 mm raindrop.

Figure 5 illustrates the fog droplet spectra (averaged from several slide samples), for the two windward Mauna Loa locations. In comparing these results with those in Figures 1 and 2, our mean droplet sizes appear

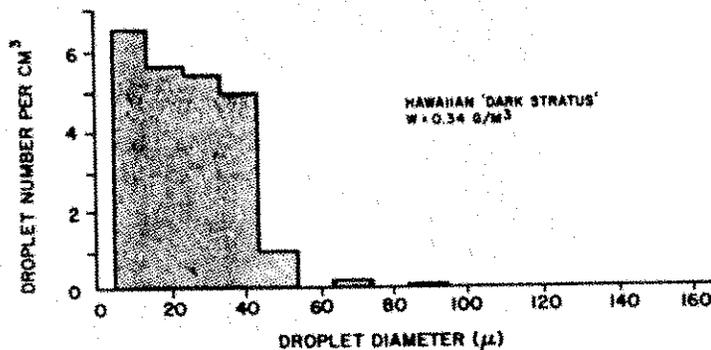
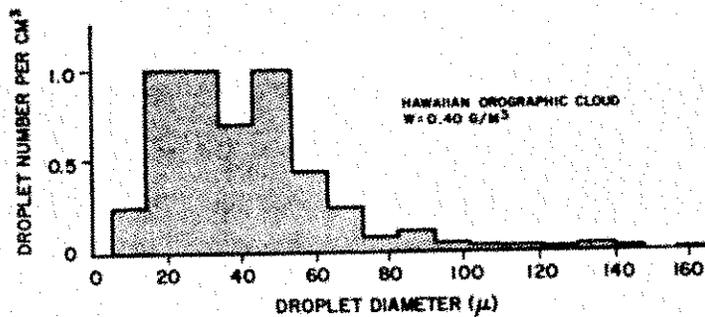
study of both windward and leeward fog conditions. Additional transects (D, E) were located on Hualalai Volcano above Kailua and in South Kona.

Primary station instrumentation included recording fog and rain gage



SOURCE: GRUNOW 1960

FIGURE 1. FOG CLOUD DROPLET SPECTRUM AS A FUNCTION OF AIR MASS TYPE IN THE ALPS: (A-B) POLAR AIR; (C) MARITIME; (D) SUBTROPICAL MARITIME



SOURCE: SQUIRES 1958

FIGURE 2. AVERAGE DROPLET SPECTRA IN OROGRAPHIC AND STRATUS CLOUDS ON WINDWARD MAUNA LOA

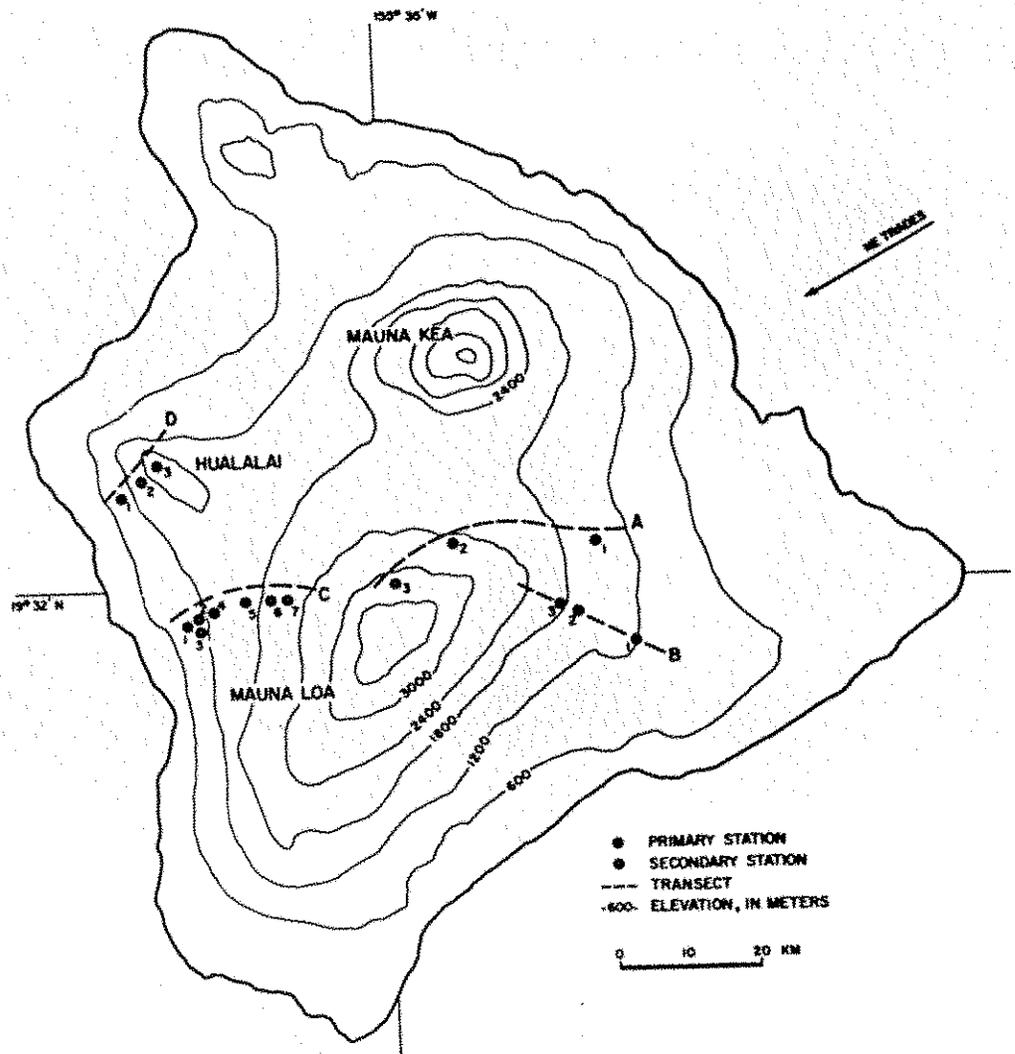


FIGURE 3. LOCATION OF FOG SAMPLING STATIONS ON THE ISLAND OF HAWAII

somewhat smaller, with the bulk of all droplets below 10 microns in diameter. The difference between our results and those in Figure 2 may in part be attributed to the differences in sampling height. Squires (1958) sampled at



FIGURE 4. MICROPHOTOGRAPH OF FOG DROPLET IMPACT CRATERS ON MAGNESIUM OXIDE COATED SLIDE. TYPICAL FOG DROPLETS SHOWN IN RELATIONSHIP TO 1 mm, RAIN DROP (CHORD AT RIGHT)

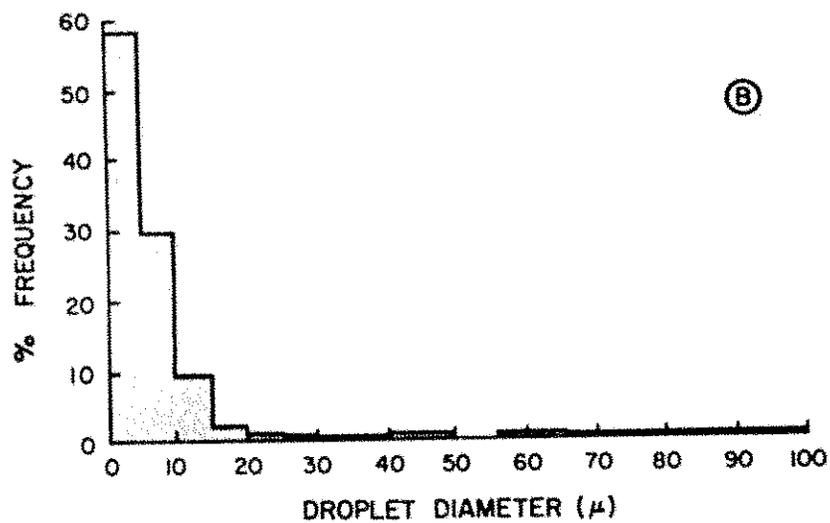
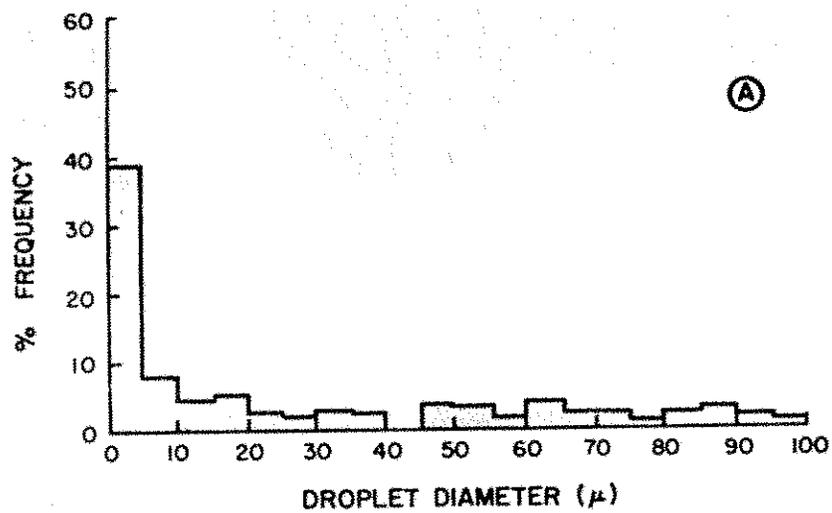


FIGURE 5. DROPLET SPECTRA FOR GROUND LEVEL UPSLOPE FOG ON WINDWARD MAUNA LOA: (A) KULANI HONOR CAMP, EL. 1580 m (AVERAGE OF 8 SAMPLES); (B) HAWAII VOLCANOES NATIONAL PARK HEAD-QUARTERS, EL. 1170 m (AVERAGE OF 5 SAMPLES)

1000 to 2000 feet (305 to 610 m) above the terrain. Samples taken in this study are at ground level, and perhaps represent an area at the very base of the cloud with poor droplet growth potential.

Regardless of the cause, the very small droplet sizes determined in this study help to further explain why simple rain gage data do not adequately portray the total moisture situation in mountain areas of Hawaii. Further, the designer of any artificial fog catchment system must be cognizant of the small droplet sizes in the choice of interception materials (see p. 16).

#### THE LOUVERED ALUMINUM SCREEN FOG GAGE

Ekern's (1964) detailed research on the comparative fog interception efficiency of various screen materials demonstrated the superior performance of wire harps and louvered aluminum shade screen. Typical wire mesh was found to be less satisfactory because of poorer drainage characteristics. Juvik and Perreira (1974) utilized louvered screen cylinders for fog catchment studies on Mauna Loa.

In the present study a gage similar to that developed by Juvik and Perreira was employed incorporating a number of design refinements based on field experiences with the earlier prototype. Figures 6 and 7 illustrate the louvered screen fog gage and the method of field mounting. The specific size dimensions of the gage are presented in Figure 8. A louvered screen cylinder (see Fig. 9 for screen detail) 12.7 cm in diameter and 40.6 cm in height was mounted into a stainless steel funnel with a diameter of 15.2 cm. This assembly was then supported on a tripod that placed the center of the screen cylinder at 3 m above the ground. Three meters was arbitrarily chosen to be representative of the mid-canopy height of subalpine scrub forests on the slopes of Mauna Kea and Mauna Loa, it was also considered that this height would minimize the effect of near surface vertical wind gradients. Companion wind measurements were also taken at 3 m. A flexible plastic tube drained the gage funnel into either a covered recording rain gage (at primary stations), or a covered, standard direct reading rain gage (at secondary stations). The louvered screen gage collected rainfall as well as horizontal traveling fog and moisture. The fog component may be derived from the difference between the louvered screen gage output, and that of a companion standard rain gage (with correction for differences in

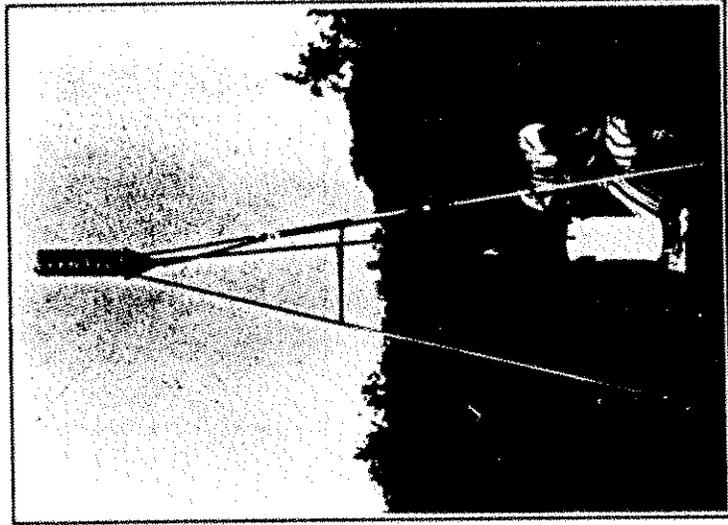


FIGURE 7. RECORDING FOG GAGE FIELD MOUNTED ON 3 m TRIPOD, DRAINING INTO TIPPING-BUCKET RAIN GAGE

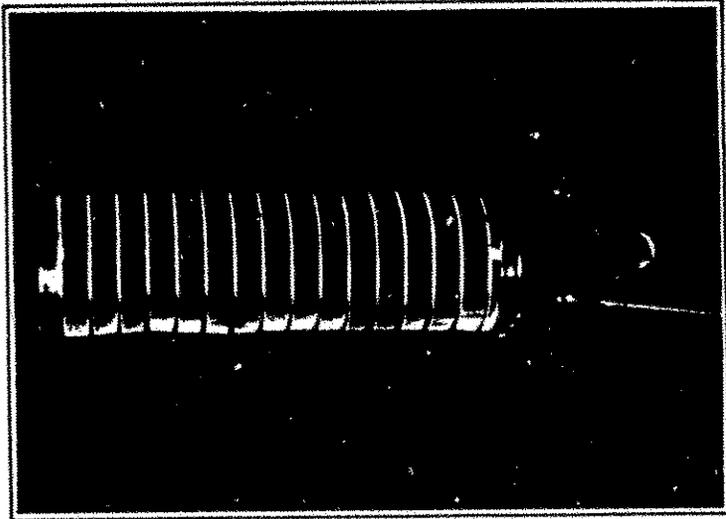


FIGURE 6. LOUVERED SCREEN FOG GAGE

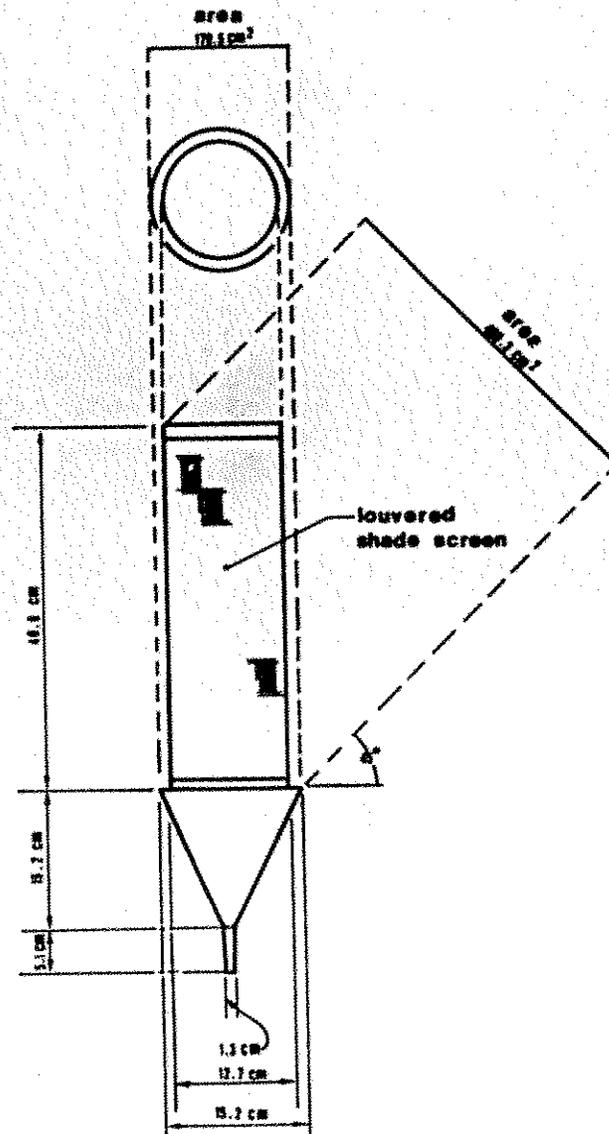


FIGURE 8. LOUVERED SCREEN FOG GAGE SCHEMATIC. DASHED LINES ILLUSTRATE CHANGE IN CATCHMENT AREA WITH CHANGE IN RAIN INCLINATION

catchment area). The interaction of rain and fog in the louvered screen gage is discussed in greater detail in a following section.

As Ekern (1964) demonstrated in his studies at Lanaihale, fog interception efficiency is largely dependent on the characteristics of the screen material used. In several previous studies on fog interception in South Africa (Nagel 1956), Europe (Grunow 1960b), and Mexico (Vogelman 1973), standard wire mesh screen gages of the Grunow type have been employed (Fig. 10).

In the present study, experiments were conducted to compare the collection efficiency of the Grunow type gage and the louvered screen gage. Weekly values of fog were computed on a "unit-area" basis for the two gages (because of different cylinder sizes) and plotted against the weekly rainfall. Based on a least square fit to the data, the louvered screen gage collected an average of 20% more fog than the Grunow gage.

#### NONVERTICAL RAINFALL AND THE LOUVERED SCREEN FOG GAGE: THE PROBLEM OF FOG DEFINITION

As discussed in the previous sections, the louvered screen fog gage collects rain as well as fog. However, simple subtraction of rainfall (collected in an adjacent rain gage) does not necessarily yield a true value for the measurement of fog if nonvertical rainfall has occurred during the sampling period. As illustrated in Figure 8 for rain-catching purposes the relative catchment area of the fog gage increases dramatically as the angle of incoming rain increases from vertical (i.e., from a catchment area of  $179.5 \text{ cm}^2$  at vertical to  $490.3 \text{ cm}^2$  at rain angle of  $45^\circ$ ). Thus, during periods of nonvertical rainfall, the fog gage will record rain values substantially above a standard rain gage, even in the absence of fog. Figure 11 portrays the predicted relationship between the fog gage and standard rain gage as a function of rain inclination angle. For example, at a rain inclination of  $45^\circ$  the fog gage would be expected (on the basis of its geometry) to collect 2.1 times as much rain water as the standard rain gage. Conversely, if the fog gage (during a sampling period) records 5 times the precipitation of a standard rain gage, we must assume that the average inclination angle of incident precipitation exceeds  $70^\circ$  in order that this difference can occur.

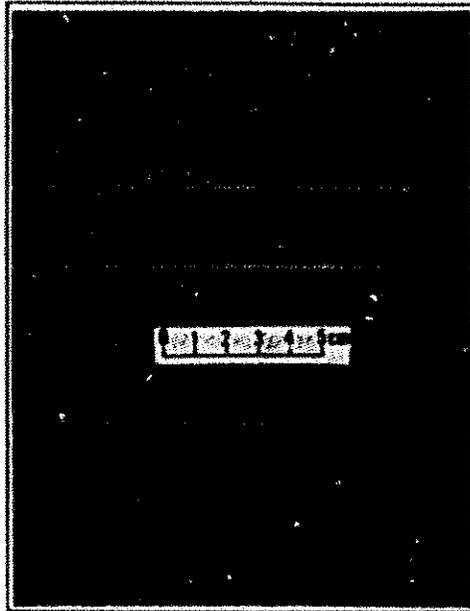


FIGURE 9. CLOSEUP OF LOUVERED ALUMINUM SHADE SCREEN

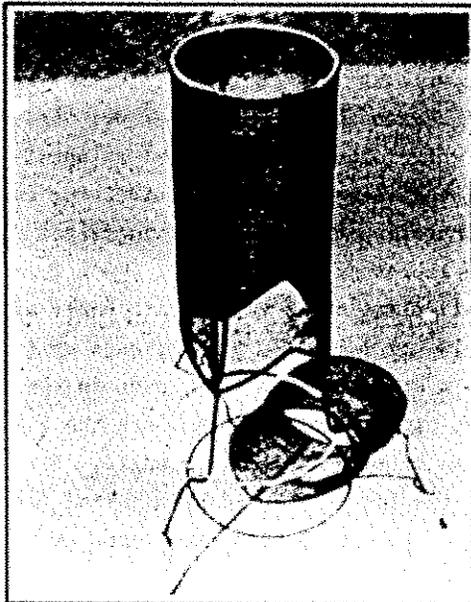


FIGURE 10. GRUNOW TYPE WIRE MESH FOG INTERCEPTOR

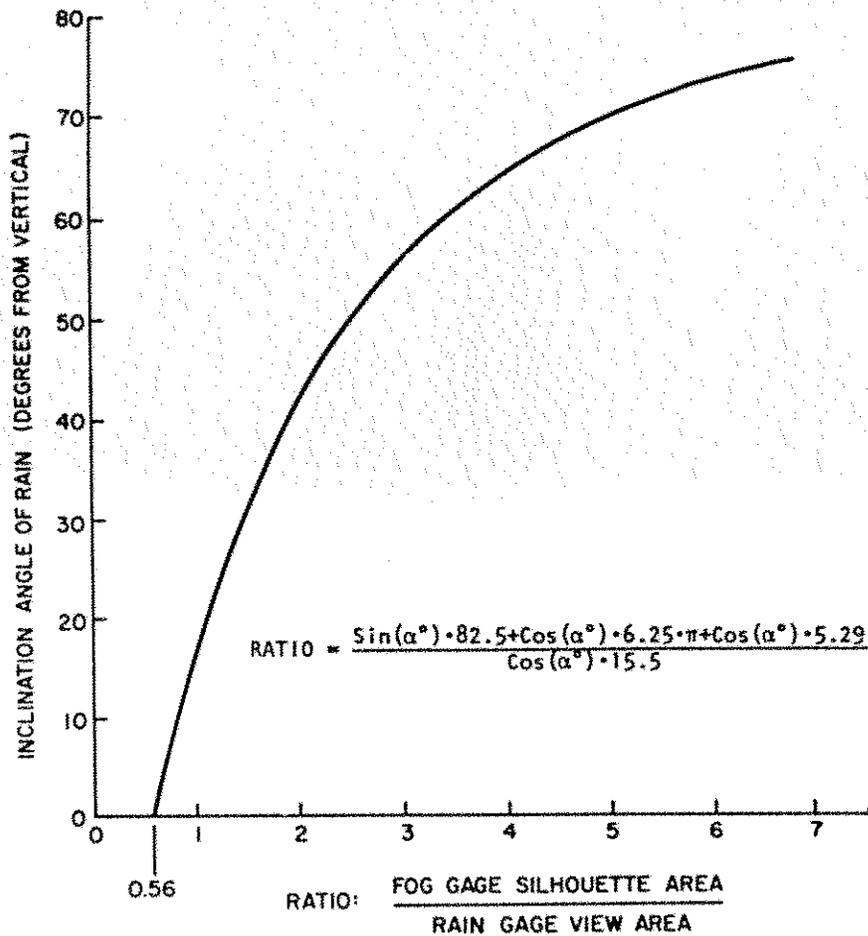


FIGURE 11. RELATIONSHIP BETWEEN FOG AND RAIN GAGE VIEW AREAS AND THE INCLINATION OF THE INCOMING RAIN

In the field monitoring program, neither the angle of rain inclination nor the average droplet sizes were directly measured. However, as Figure 12 illustrates, with the addition of wind speed, inclination angle and droplet size can be physically related. This relationship is important because, as noted above, greater water collection by the fog gage is not in itself proof of the presence of fog.

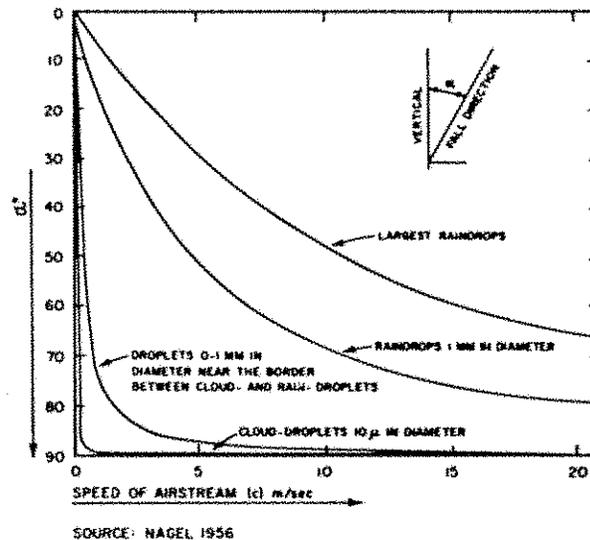


FIGURE 12. PHYSICAL RELATIONSHIPS BETWEEN WIND SPEED, DROPLET INCLINATION, AND SIZE

With wind speed data, and using the relationships presented in Figures 11 and 12, it is possible to roughly approximate the average droplet size during any sample period. The data presented in Figure 13 can be used to illustrate the method for droplet size determination. The figure presents raw output from the tipping-bucket rain and fog gages at a primary station (B-3) on windward Mauna Loa (el. 2010 m). During episode No. 1, the fog gage tipped 13 times and the rain gage 16 times for a ratio of .81. Under vertical rainfall conditions a ratio of .56 would be expected since the fog gage has a cross sectional area equal to 56% of the rain gage. Plotting .81 in Figure 11 indicates that an inclination angle of roughly  $8^\circ$  is required to explain the measured ratio. If this value of  $8^\circ$  and the average wind speed for the period (2 m/sec) are then plotted in Figure 12, a drop size estimate



corresponding to "large size raindrops" results.

In episode No. 2 (Fig. 13) the ratio of fog to rain is 5.0 and plotting this in Figure 11 indicates an inclination angle of at least  $70^\circ$  to account for this ratio. Since the average wind speed during this period was only 1 m/sec and the inclination angle estimated at more than  $70^\circ$ , it is impossible for large raindrops to have been involved (Fig. 12). At a wind speed of 1 m/sec only drops smaller than 100 to 200 microns will fall at an angle exceeding  $70^\circ$ . Thus, it is possible to state with confidence that episode No. 2 represents a period of fog and mist rather than nonvertical "large drop" rainfall.

By programming the relationships presented in Figures 11 and 12 into data analysis computer programs, it is possible to delimit fog periods and separate these from nonvertical rainfall episodes, a refinement not attempted in previous fog studies.

#### FOG SAMPLING NETWORK

In an effort to monitor the contribution of fog precipitation in mountain areas on Hawaii, an extensive network of louvered screen fog gages were established on the island of Hawaii. While the present study is concerned primarily with research methodology rather than the analysis of field data, details of the fog monitoring program are presented here in the context of sampling methodology.

Two primary concerns dictated the development of the sampling network. First, sampling was largely restricted to windward and leeward mountain areas with relatively low direct rainfall, where it was hypothesized that the contribution of fog might represent a relatively large fraction of the total precipitation. Such areas represent the greatest potential for the development of large scale artificial fog catchment systems. Secondly, the accessibility problem was a prime consideration as much of the higher slopes of Mauna Loa are rugged, roadless lava lands. Sampling stations were necessarily restricted to areas with roads or jeep trail accesses.

Figure 3 identifies the location of fog sampling stations on the island of Hawaii. The major transects, A, B, and C (composed of 13 sampling stations), were oriented east-west on the slopes of Mauna Loa for comparative

study of both windward and leeward fog conditions. Additional transects (D, E) were located on Hualalai Volcano above Kailua and in South Kona.

Primary station instrumentation included recording fog and rain gage (Weather Measure Corp. tipping-bucket gage No. 501) logged on multi-channel event recorders (Rustrak Model No. 292) (see Fig. 13 for typical recorder output). Wind speed and direction were monitored using a Field Recording Wind Set (R.M. Young Co. Model No. 6405). The standard setup for primary stations is illustrated in Figures 14 and 15. Secondary stations shown on the map in Figure 3 were equipped with manual reading rain and fog gages, and monitored at weekly intervals.

#### COMPUTER ANALYSIS PROGRAM

The fog analysis computer program (Appendix A) reduces 15-minute data samples of wind and precipitation parameters (compiled at primary recording stations) into a form useful for statistical manipulation and graphic display. The data summaries include hourly, daily, and total sample period averages for rain and fog precipitation, broken down into five categories: (1) periods with fog and rain, (2) periods with rain (irrespective of fog), (3) periods of fog (irrespective of rain), (4) periods of rain only, and (5) periods of fog only.

Analysis of the "rain only" and "fog only" episodes, in particular, is useful in characterizing precipitation episodes, both temporally and spatially. Figure 16 illustrates the temporal frequency of "fog only" episodes at two stations on windward Mauna Loa for a sample 15-day period. The striking difference between the two stations with respect to temporal occurrence of fog maxima is illustrative of the complex meteorology in mountain areas of Hawaii. Table 2 portrays the five rain and fog categories for this same sample period as a function of prevailing wind direction. As can be seen in the Table, during the sample period most rain and fog were associated with winds from the south and southeast in the case of Station No. B-3 while the pattern was more complex at Station No. B-1, where fog was derived primarily from the east and northeast. This sample period with a large southern wind component, represents a Kona storm situation (low pressure system between Hawaii and the subtropical high pressure cell to the north).

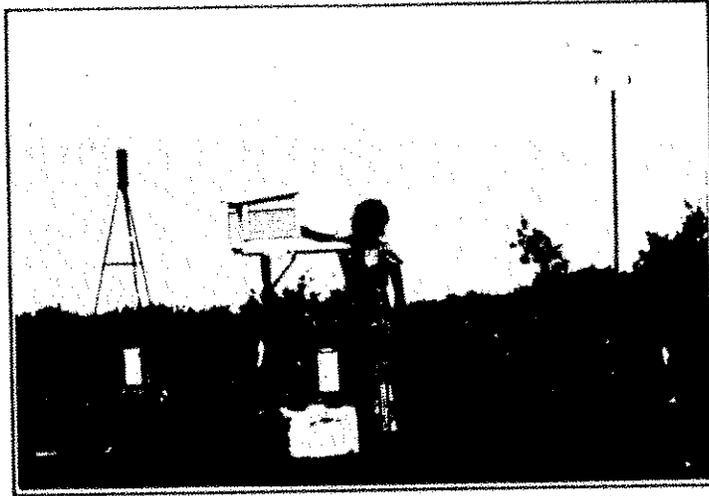


FIGURE 14. TYPICAL PRIMARY STATION WITH FULLY AUTOMATIC RECORDING EQUIPMENT OF FOG, RAIN, WIND SPEED, AND DIRECTION

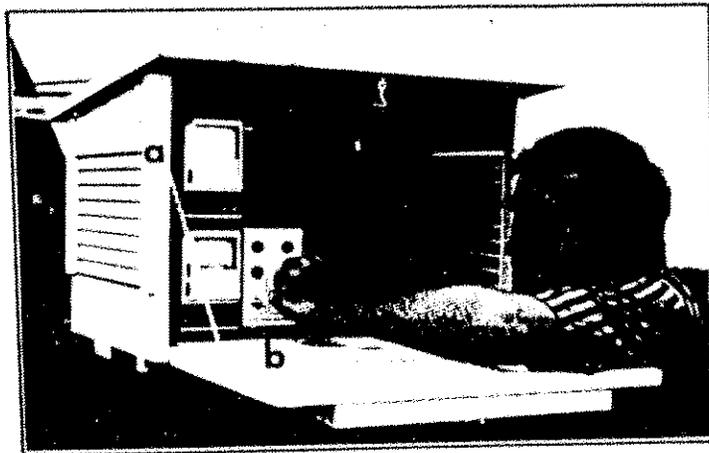


FIGURE 15. PRIMARY STATION INSTRUMENT SHELTER: (A) MULTI-CHANNEL TIPPING-BUCKET GAGE EVENT RECORDER; (B) WIND SPEED AND DIRECTION RECORDER

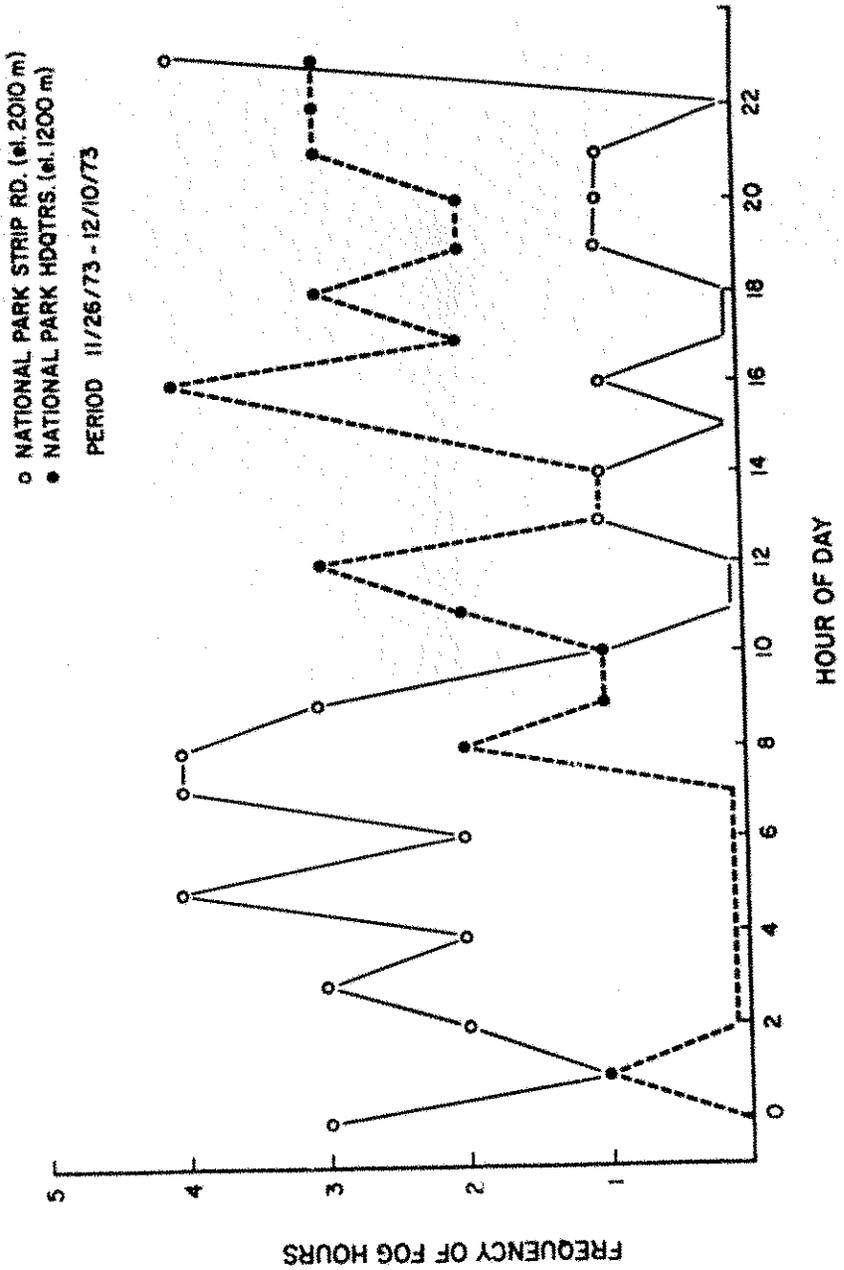


FIGURE 16. SAMPLES COMPUTER OUTPUT OF TEMPORAL FOG FREQUENCY FOR A 15 DAY PERIOD ON WINDWARD MAUNA LOA

TABLE 2. WIND DIRECTION CATEGORIES AGAINST 15 MIN. INTERVAL PERIODS OF RAIN AND FOG

STATION NO. B-3 (NATIONAL PARK - STRIP RD.)									
	N	NE	E	SE	S	SW	W	NW	TOTAL NO. OF PERIODS
FOG AND RAIN	2 (1%)	3 (1.5%)	6 (3.1%)	78 (40.8%)	89 (46.5%)	10 (5.2%)	1 (.52%)	2 (1%)	191
RAIN (IRRE-SPECTIVE FOG)	2 (.9%)	4 (1.9%)	6 (2.9%)	78 (38.8%)	96 (47.7%)	10 (4.9%)	1 (.49%)	4 (1.9%)	201
FOG (IRRE-SPECTIVE RAIN)	2 (.87%)	4 (1.7%)	8 (3.5%)	84 (36.8%)	112 (49.0%)	10 (4.3%)	1 (.43%)	7 (3.0%)	228
RAIN ONLY	0	1 (10.0%)	0	0	7 (70.0%)	0	0	2 (20.0%)	10
FOG ONLY	0	1 (2.7%)	2 (5.4%)	6 (16.2%)	23 (62.1%)	0	0	5 (13.5%)	37

STATION NO. B-1 (NATIONAL PARK HQTRS.)									
	N	NE	E	SE	S	SW	W	NW	TOTAL NO. OF PERIODS
FOG AND RAIN	1 (.46%)	7 (3.2%)	6 (2.7%)	103 (47.6%)	43 (20.0%)	21 (9.7%)	32 (14.8%)	3 (1.4%)	216
RAIN (IRRE-SPECTIVE FOG)	1 (.43%)	8 (3.5%)	6 (2.6%)	104 (45.6%)	47 (20.6%)	22 (9.6%)	37 (16.2%)	3 (1.3%)	228
FOG (IRRE-SPECTIVE RAIN)	1 (.39%)	17 (6.6%)	17 (6.6%)	104 (40.7%)	50 (19.6%)	27 (10.5%)	36 (14.1%)	3 (1.1%)	255
RAIN ONLY	0	1 (8.3%)	0	1 (8.3%)	4 (33.3%)	1 (8.3%)	5 (41.6%)	0	12
FOG ONLY	0	10 (25.6%)	11 (28.2%)	1 (2.5%)	7 (12.9%)	6 (15.3%)	4 (10.2%)	0	39

The computer analysis program summarizes the relationship between both wind direction and speed against precipitation episodes on an hourly, daily, and monthly basis. Knowledge of wind characteristics during precipitation episodes is particularly important to the possible future development of large scale fog catchment systems, insofar as catchment orientation could greatly influence the efficiency of water collection.

#### SUMMARY AND CONCLUSIONS

This study was undertaken with the objective of developing and field testing research methods and materials useful in a multi-faceted investigation of Hawaiian upslope fog.

Major accomplishments of the research included:

1. The development and field testing of an improved louvered screen fog gage.
2. The development of an approximation method for separating the contribution of nonvertical rainfall and fog, and estimating the average droplet sizes for precipitation episodes.
3. The establishment of an extensive fog sampling network on the island of Hawaii.
4. The development of a computer program for fog data analysis.

The present study has succeeded in its objective of developing useful research methods. The application of these research approaches during ongoing and future phases of the fog project should yield useful information on the water balance of mountain areas, and the feasibility of developing large scale artificial fog catchment systems in areas of chronic water shortage.

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## APPENDIX

## Fog Analysis Computer Program

```

001     DIMENSION IM(4),RN(4),FG(4),WS(4),WD(4)
        DIMENSION RTOT(25),FTOT(25),R(25),F(25),AWS(25),HWS(25),SWS(25)
1     IFRP(25),IRP(25),IFP(25),IRNLY(25),IFNLY(25),WN(25),JN(24),
2     AR(25),AF(25),TR(25),WA(25),DUM(2)
003     DIMENSION WSC(25,5),WDC(25,8),WDSC(25,5,8),I TFR(97,5)ISFR(6,5)
1     IDFR(9,5),IWDS(25,5,8),ISC(25,5),IDC(25,8)IB(2010),B(1605)
004     COMMON /RF/ IFRP,IRP,IFP,IRNLY,IFNLY,ITFR,ISFR,IDFR,IWDS,ISC,IDC,
005     COMMON RTOT,FTOT,WA,R,F,AWS,HWS,SWS,WSC,WDC,WN,WDSC,AW,HW,SW,AR,
1     AF,RTMP,FTMP
006     EQUIVALENCE (IB(1),IFRP(1)),(B(1),RTOT(1))
007     LOGICAL END, NEWSTA
008     DATA END/.TRUE./, NEWSTA/.FALSE./
009     DATA DATMIS/-0.00001/,DUM/2*-2./
010     DATA D1,D2,D3,D4,D5,D6,D7,D8/23.,67.,112.,157.,202.,247.,292.,
1     337./,S1,S2,S3,S4/1.,3.,5.,7./
011     DATA IERR,IERRM/0,10/,WSMAX,LYR/29.,4/

C
012 100 K = 0
013     LOOP = C
014 400 K = K+1
015     IF(NEWSTA) GO TO 700
016 500 READ 600, IS,IMON,IDY,IYR,IH,(IM(J),RN(J),FG(J),WS(J),WD(J),J=1,4)
017 600 FORMAT(I1,2I2,I1,I2,4(I2,2F2.0,F3.1,F3.0,5X))
018     IF((IS.EQ.0).AND.(IMON.EQ.0)) GO TO 5000
019     IF((IS.LT.0).OR.(IMON.LT.1).OR.(IMON.GT.12).OR.(IDY.LT.1)
1     .OR.(IDY.GT.31).OR.(IYR.LT.3).OR.(IYR.GT.LYR).OR.(IH.LT.0)
2     .OR.(IH.GT.23)) GO TO 9600
020     DO 650 I=1,4
021     IF((IM(I).LT.0).OR.(IM(I).GT.45).OR.(RN(I).LT.0.).OR.(FG(I).LT.0.)
1     .OR.(WS(I).LT.0.).OR.(WS(I).GT.WSMAX).OR.(WD(I).LT.0.)
2     .OR.(WD(I).GT.360.)) GO TO 9600
022 650 CONTINUE
023     IH=IH + 1
024     IF (K.EC.1) GO TO 700
025     IF (IS.NE.ISL) GO TO 4900
026     IF (IDY.NE.IDL .OR. IMON.NE.IML) GO TO 6100
027     GO TO 1000
028 700 ISL = IS
029     IML = IMON
030     IDL = IDY
031     IYL = IYR
032     IF(.NOT.(END)) GO TO 1000
033     DO 800 I = I, 1605
034     IB(I) = 0
035     B(I) = C.
036 800 CONTINUE
037     DC 900 I =1606,2010
038     IB(I) =0
039 900 CONTINUE
040     ISI = IS

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041     IMI = IMON
042     IDI = IDY
043     IYI = IYR
044     NEWSTA = .FALSE.
045     END = .FALSE.

```

C

```

046 1000 DO 3500 I=1,4
047     L = 0
048     WS(I) = 0.4472 * WS(I)
049     AWS(IH) = AWS(IH) + 0.25 * WS(I)
050     IF((RN(I).EQ.O.).AND.(FG(I).EQ.O.)) GO TO 1300
051     RTOT(IH) = RTOT(IH) + 0.254 * RN(I)
052     FTOT(IH) = FTOT(IH) + 0.254 * FG(I)
053     IF((RN(I).EQ.O.).OR.(FG(I).EQ.O.))GO TO 1100
054     IFRP(IH) = IFRP(IH) + 1
055     IRP(IH) = IRP(IH) + 1
056     IFP(IH) = IFP(IH) + 1
057     L = 1
058     GO TO 1300
059 1100 IF(FG(I).EQ.O.) GO TO 1200
060     IFP(IH) = IFP(IH) + 1
061     IFNLY(IH) = IFNLY(IH) + 1
062     L = 3
063     GO TO 1300
064 1200 IRP(IH) = IRP(IH) + 1
065     IRNLY(IH) = IRNLY(IH) + 1
066     L = 2
067 1300 IF(WS(I).LT.S1) GO TO 1700
068     IF(WS(I).GT.S2) GO TO 1400
069     NWSN = 2
070     GO TO 1900
071 1400 IF(WS(I).GT.S3) GO TO 1500
072     NWSN = 3
073     GO TO 1900
074 1500 IF(WS(I).GT.S4) GO TO 1600
075     MWSN = 4
076     GO TO 1900
077 1600 NWSN = 5
078     GO TO 1900
079 1700 NWSN = 1
080 1900 IF(WD(I).GT.D4) GO TO 2300
081     IF(WD(I).GT.D2) GO TO 2100
082     IF(WD(I).LT.D1) GO TO 2000
083     NWDN = 2
084     GO TO 2800
085 2000 NWDN = 1
086     GO TO 2800
087 2100 IF(WD(1).GT.D3) GO TO 2200
088     NWCN = 3
089     GO TO 2800
090 2200 NWCN = 4
091     GO TO 2800
092 2300 IF(WD(I).GT.D6) GO TO 2500
093     IF(WD(I).GT.D5) GO TO 2400

```

```

094      NWDN = 5
095      GO TO 2800
096 2400  NWDN = 6
097      GO TO 2800
098 2500  IF(WD(I).GT.D7) GO TO 2600
099      NWDN = 7
100      GO TO 2800
101 2600  IF(WD(I).GT.D8) GO TO 2000
102      NWDN = 8
103 2800  CONTINUE
104      WSC(IH,NWSN) = WSC(IH,NWSN) + 25
105      WDC(IH,NWDN) = WDC(IH,NWDN) + 25
106      WDSC(IH,NWSN,NWDN) = WDSC(IH,NWSN,NWDN) + 25
107      IF(L.EC.O) GO TO 3500
108      IFM = 4*IH + I - 4
109      IF(L.GT.1) GO TO 3000
110      DO 2900 K = 1,3
111          ITFR(IHM,K) = ITFR(IHM,K) + 1
112          ISFR(NWSN,K) = ISFR(NWSN,K) + 1
113          IDFR(NWDN,K) = IDFR(NWDN,K) + 1
114 2900  CONTINUE
115      GO TO 3500
116 3000  DO 3100 K = 1,5,2
117          ITFR(IHM,K) = ITFR(IHM,K) + 1
118          ISFR(NWSN,K) = ISFR(NWSN,K) + 1
119          IDFR(NWDN,K) = IDFR(NWDN,K) + 1
120 3100  CONTINUE
121 3500  CONTINUE
122      WA(IH) = WA(IH) + 1
123      WN(IH) = WN(IH) + 1
124      HWS(IH) = HWS(IH) + AMAX1(WS(1),WS(2),WS(3),WS(4))
125      SWS(IH) = SWS(IH) + AMIN1(WS(1),WS(2),WS(3),WS(4))
126      GO TO 400
127 4900  NEWSTA = .TRUE.
128 5000  IF(END) GO TO 9900
129      END = .TRUE.
130 6100  DC 6200 I=1,24
131      IF(WA(I).GT.O.) GO TO 6150
132      RTOT(I) = DATMIS
133      FTOT(I) = DATMIS
134      GO TO 6200
135 6150  RTOT(25) = RTOT(25) + RTOT(I)
136      FTOT(25) = FTOT(25) + FTOT(I)
137      R(I) = R(I) + RTOT(I)
138      F(I) = F(I) + FTOT(I)
139 6200  CONTINUE
140      R(25) = R(25) + RTOT(I)
141      F(25) = F(25) + FTOT(I)
142      IF(LOOP.GT.O) GO TO 6500
143      PRINT 6300,ISL
144      PRINT 6400
145 6500  PRINT 6600,IML,IDL,IYL,RTOT,FTOT,
146      IF(END) GO TO 7000

```

```

147      DO 6800 I=1,75
148 6800  B(I) = 0
149      LOOP = LOOP + 1
150      K = 1
151      GO TO 700
152 7000  Z = 24
153      DO 5700 IT=1,
154      W = WN(IT)
155      IF(W.GT.O.) GO TO 5400
156      Z = Z - 1
157      R(IT) = DATMIS
158      F(IT) = DATMIS
159      AR(IT) = DATMIS
160      AF(IT) = DATMIS
161      AWS(IT) = DATMIS
162      HWS(IT) = DATMIS
163      SWS(IT) = DATMIS
164      GO TO 5700
165 5400  AR(IT) = R(IT)/W
166      AF(IT) = F(IT)/W
167      RTMP = RTMP + AR(IT)
168      FTMP = FTMP + AF(IT)
169      AWS(IT) = AWS(IT) / W
170      HWS(IT) = HWS(IT) / W
171      SWS(IT) = SWS(IT) / W
172      AW = AW + AWS(IT)
173      HW = HW + HWS(IT)
174      SW = SW + SWS(IT)
175      DO 5500 I=1,5
176      WSTMP = WSC(IT,I) / W
177      ISC(IT,I) = WSTMP + 0.5
178      WSC(25,I) = WSC(25,I) + WSTMP
179 5500  CONTINUE
180      DC 5600 J=1,8
181      WDTMP = WDC(IT,J) / W
182      IDC(IT,J) = WDTMP + 0.5
183      WDC(25,J) = WDC(25,J) + WDTMP
184      DO 5600 I = 1,5
185      WTMP = WDSC(IT,I,J) / W
186      IWDS(IT,I,J) = WTMP + 0.5
187      WDSC(25,I,J) = WDSC(25.I,J) + WTMP
188 5600  CONTINUE
189 5700  CONTINUE
190      AR(25) = RTMP
191      AF(25) = FTMP
192      DO 5800 I=1,5
193      ISC(25,I) = WSC(25,I) / Z + 0.5
194 5800  CONTINUE
195      DO 5900 J=1,8
196      IDC(25,J) = WDC(25,J) / Z + 0.5
197      DO 5900 I=1,5
198      IWDS(25,I,J) = WDSC(25,I,J) / + 0.5
199 5900  CONTINUE

```

```

200     AWS(25) = AW / Z
201     HWS(25) = HW / Z
202     SWS(25) = SW / Z
203     DO 6000 I=1,5
204     DO 6000 J=1,96
205     ITFR(97,I) = ITFR(97,I) + ITFR(J,I)
206 6000 CONTINUE
207     DO 6020 I=1,5
208     DO 6020 J=1,5
209     ISFR(6,I) = ISFR(6,I) + ISFR(J,I)
210 6020 CONTINUE
211     DO 6040 I=1,5
212     DO 6040 J=1,8
213     IDFR(9,I) = IDFR(9,I) + IDFR(J,I)
214 6040 CONTINUE
215     PRINT 7420
216     PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
217     PRINT 6400
218     PRINT 7400 R,F
219     PRINT 7410
220     PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
221     PRINT 6400
222     PRINT 7400, AR,AF
223     DO 7250 I=1,24
224     JN(I) = I -1
225 7250 CONTINUE
226     PRINT 7420
227     PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
228     PRINT 7440, (R(I),I=1,24, (F(I),I=,24)
229     CALL HIST(R,F,24
230     PRINT 7445, JN
231     PRINT 7446
232     PRINT 7460
233     PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL,
234     PRINT 7440,(AR(I),I=1,24, (AF(I),I=1,24)
235     CALL HIST(AR,AF,24)
236     PRINT 7445, JN
237     PRINT 7446
238     DO 7300 I=1,24
239     IFRP(25) = IFRP(25) + IFRP(I)
240     IRP(25) = IRP(25) + IRP(I)
241     IFP(25) = IFP(25) + IFP(I)
242     IRNLY(25) = IRNLY(25) + IRNLY(I)
243     IFNLY(25) = IFNLY(25) + IFNLY(I)
244 7300 CONTINUE
245     PRINT 7450
246     PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
247     PRINT 6400
248     PRINT 7500, IFRP,IRP,IFP,IRNLY,IFNLY
249     PRINT 7600
250     PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
251     II = 1
252     IN = 32

```

```

253      DO 7850 MM=1,2
254      PRINT 7700, JN(I), I=1,8
255      PRINT 7800, ((ITFR(I,J), I=II, IN, J=5)
256      II = II + 32
257      IN = IN + 32
258      DO 7850 I = 1,8
259      JN(I) = JN(I) + 8
260 7850  CONTINUE
261      IN = IN + 1
262      PRINT 7700, (JN(I), I=1,8
263      PRINT 7880, ((ITFR(I,J), I=II, IN), J=1,5)
264      DO 7910 I=1,24
265      TR(I) = IFRP(I)
266      R(I) = IRP(I)
267      F(I) = IFP(I)
268      AR(I) = IRNLY(I)
269      AF(I) = IFNLY(I)
270      JN(I) = I-1
271 7910  CONTINUE
272      PRINT 7930
273      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
274      PRINT 7915, (IFRP(I), I=1,24
275      CALL HIST(TR, DUM, 24)
276      PRINT 7445, JN
277      PRINT 7940
278      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
279      PRINT 7920, (IRP(I), I=1,24, (IFP(I), I=1,24
280      CALL HIST(R, F, 24)
281      PRINT 7445, JN
282      PRINT 7950
283      PRINT 7960
284      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
285      PRINT 7920, (IRNLY(I), I=1,24), IFNLY(I), I=1,24)
286      CALL HIST(AR, AF, 24)
287      PRINT 7445, JN
288      PRINT 7970
289      PRINT 7900
290      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
291      PRINT 8000, S1, S1, S2, S2, S3, S3, S4, S, 4
292      PRINT 8100, ISFR
293      PRINT 8200
294      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
295      PRINT 8300
296      PRINT 8400, IDFR
297      PRINT 8500
298      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
299      PRINT 6400
300      PRINT 8600, AWS, HWS, SWS
301      PRINT 8700
302      PRINT 7200, IMI, IDI, IYI, IML, IDL, IYL, ISL
303      PRINT 6400
304      PRINT 8800, S1, (ISC(I,1), I=1,25), S1, S2, (ISC(I,2), I=1,25), S2, S3,
1 (ISC(I,3), I=1,25), S3, S4, (ISC(I,4), I=1,25), S4, (ISC(I,5), I=1,25)

```

```

305 PRINT 8900
306 PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
307 PRINT 6400
308 PRINT 9000, IDC
309 PRINT 9100
310 PRINT 7200, IMI,IDI,IYI,IML,IDL,IYL,ISL
311 DO 9400 J=1,8
312 IF(J.EC.C.5) PRINT 9300
313 PRINT 6400
314 IF(J.EQ.1) PRINT 9310
315 IF(J.EQ.2) PRINT 9320
316 IF(J.EQ.3) PRINT 9330
317 IF(J.EQ.4) PRINT 9340
318 IF(J.EQ.5) PRINT 9350
319 IF(J.EQ.6) PRINT 9360
320 IF(J.EQ.7) PRINT 9370
321 IF(J.EQ.8) PRINT 9380
322 PRINT 8800,S1,(IWDS(I,1,J),I=1,25),S1,S2,IWDS(I,2,J,I=1,25),S2,
1 S3,(IWDS(I,3,J),I=1,25),S3,S4,(IWDS(I,4,J),I=1,25),S4,(IWDS(I,5,J
2),I=1,25)
323 PRINT 9300
324 9400 CONTINUE
325 PRINT 9500
326 GO TO 100
327 9600 IERR = IERR + 1
328 PRINT 9610, IS,IMON,IDY,IYR,IH
329 IF(IERR.NE.IERRM) GO TO 500
330 PRINT 9620, IERR
331 9900 PRINT 9990
332 STOP
333 6300 FORMAT(1H1,9X,'STATION NUMBER ',I1,' :',26X,'DAILY RAIN AND FOG B
1Y HOURS (MM) ',/'0 DATE',58X,'HOURS OF DAY')
334 6400 FORMAT(1H,8X,'00 01 02 03 04 05 06 07 08 09 1
10 11 12 13 14 15 16 17 18 19 20 21 22 23
2 TOTAL')
335 6600 FORMAT(IH-,I2,'-',12,'-7',I1/' RAIN',24F5.1,F6.1/'0 FOG',24F5.
11,F6.1)
336 7200 FORMAT(IH+,70X,12,'-',12,'-7',I1,' TO ',12,'-',12,'-7',I1,
1 ' AT STATION ',I1/)
337 7400 FORMAT(1H-, ' RAIN ',24F5.1,F6.0/1H0,' FOG ',24F5.1,F6.0)
338 7410 FORMAT(IH-//31X,'HOURLY AVERAGE RAIN AND FOG FOR PERIOD')
339 7420 FORMAT(IH1,29X,'RAIN AND FOG TOTALS BY HOURS FOR PERIOD')
340 7440 FORMAT(IHC,2X,'MM RN',24F5.1/3X,'MM FG',24F5.1)
341 7445 FORMAT(IH ,6X,24I5/63X,'HOURS OF DAY')
342 7446 FORMAT(IH ,5X,'0 = RAIN (MM)'/6X,'X = FOG (MM)')
343 7450 FORMAT(1H1/26X,'PERIODS OF RAIN AND FOG BY HOURS FOR PERIOD')
344 7460 FORMAT(1H1,30X,'HOURLY AVERAGE RAIN AND FOG FOR PERIOD')
345 7500 FORMAT('-R + F',24I5,17/'ORAIN ',24I5,17/'OFOG ',24I5,17/'OR ONLY
1',I4,23I5,17/'OF ONLY',14,23I5,17)
346 7600 FORMAT(1H-//18X,'PERIODS OF RAIN AND FOG BY QUARTER HOURS FOR PERI
1OD')
347 7700 FORMAT(IH ,8114,13X,'TOTAL')

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