Rainfall Trends in Hawaii^{1,2}

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ABSTRACT

A recent study in Queensland, Australia, associates long-term downward trends in rain amount with the productivity of the local sugarcane industry. The relationship is attributed to an increasing colloidal stability in the clouds caused by additional cloud condensation nuclei shown to be present in the smoke coming from local cane-harvesting fires.

As an additional test of the hypothesis, the rainfall records of several sugar-producing areas in Hawaii are examined where burning prior to harvesting is also practiced. Two physically similar leeward coastal areas were selected for comparison, one because it is downwind from a major cane-growing region and the other because it is not. The data suggest a downward trend in rainfall over periods of 30–60 years at *both* areas, but the trends are not statistically significant. However, the records for areas along the windward coastal regions of the two northwesternmost islands indicate an upward trend. It is concluded that factors other than cane-fire smoke are probably involved in any rainfall trends which may exist.

1. Introduction

Warner (1968) carried out a practical test of the idea that cumulus shower-type clouds are less likely to produce rain if the number of cloud droplets in them is increased. This idea evolved from the earlier work of Squires (1958) and Squires and Twomey (1960) on differences in the droplet populations of marine and continental cumuli and on the various sources of cloud condensation nuclei. Later, Warner and Twomey (1967) found that smoke from sugarcane harvesting operations in Queensland, Australia, increased cloud-droplet number in local cumulus clouds. This result led Warner to speculate that local rainfall might be affected. He examined rainfall records in the cane-growing area for trends which could be attributed to the growth of the sugar industry and the consequent increase in smoke production. Warner (1968) reported a reduction in rainfall "consistent with the hypothesis that through their activity as condensation nuclei the smoke particles result in great increases in concentration and consequent reduction in the size of cloud droplets, thereby hindering the coalescence process of rain formation." Warner used only data from rainfall occurring during onshore (sea) winds. Coastal rainfall records were used to indicate that the trends were not inherent in the atmosphere flowing from over the sea prior to its passage over the cane fields.

Our purpose here is to present the results of a similar rainfall study made in sugarcane-growing areas of Hawaii where burning prior to harvesting has been practiced since about 1910 (Pratt, 1925). We hoped to test Warner's hypothesis in an area where more rain-gage records are available and where climatological conditions are probably steadier due to the oceanic environment. We are assuming that the burning Hawaiian sugarcane produces about the same number of cloud nuclei per gram of leaf as are produced by the Australian cane, i.e., $\sim 5 \times 10^{12}$ [see Warner and Twomey (1967, p. 706)], although there are differences in the nature of the crop and in the conditions under which it is burned and harvested. No records of amounts of cane burning are available in Hawaii. We have had to assume an increase in smoke production about proportional to the approximate threefold increase in tonnage of sugarcane harvested³ during the period of rain record (1910–60). In his Queensland study, Warner (1968) indicates an approximate fourfold cane production increase during the same time interval.

2. Areas selected

Fig. 1 shows the cane-growing areas and elevation contours of the major Hawaiian islands, and Figs. 2 and 3 show the areas on Hawaii⁴ and Maui selected to test Warner's hypothesis. Area A on Hawaii (see Fig. 1),

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³ Hawaiian Sugar Planters Association, Honolulu.

⁴ "Hawaii" as used hereafter refers to the island of Hawaii. When reference is to the state, State of Hawaii or the Hawaiian Islands will be used.

FIG. 1. Chart of major islands, showing elevation contours (ft), sugarcane growing regions (fine-hatched areas) and the rainfall test locations A and B. The position, number, and rainfall trend index of the windward coastal rainfall stations are indicated. See text for explanation of index.

containing 40 useable long-term raingages (Fig. 2), was thought to be most likely to reveal smoke effects upon rainfall, should any exist, since it lies downwind (westward) from a cane-producing area. In contrast to Area A, Area B on Maui (Fig. 1), containing 18 useful long-term raingages (see Fig. 3), is on the windward side (east) of the cane-growing regions and is relatively free of cane-fire smoke. Area B is therefore regarded as a control.

Winds over Areas A and B are generally deflected parallel to the contours around the north and north-west flanks of large mountains (see altitude contours on Fig. 1) and subsequently through "saddles" between the mountains. Wind speed and direction measurements in these areas during the period concerned are very sparse. We have used the studies of Leopold (1949, a, b) and Lavoie (1967), and knowledge of the layout of local airstrips on the plantations. However, for long-term wind direction over the areas, we have relied mainly on the persistence of the northeast trade

winds as revealed by the surface weather charts of the North Pacific. In other words, we have had to assume, during the daylight hours when most of the burning is done, that the direction of the air flow has been largely right to left across Areas A and B (see Figs. 2 and 3), carrying smoke toward A from the cane fields and away from B.

Following Warner (1968), we have used certain windward coastal station rain records (see locations on Fig. 1) as a test of possible long-term trends inherent in the trade-wind atmosphere shortly after passage of the air stream from over the windward sea. These coastal stations were selected because they are largely in regions of onshore wind flow, where rainfall is relatively unlikely to be influenced by island sources of cloud nuclei. The extent to which the rainfall at these coastal stations is independent of land influences is uncertain. We can reasonably assume, however, that it is markedly less affected than is the rainfall at most of the stations of Areas A and B.

FIG. 2. Chart of Hawaii, presenting isohyetal lines and the number, location, and trend index of rainfall stations in test area A.

3. Station selection

Long-term trends in rainfall amounts sampled at individual stations can be brought about by many factors in addition to differences in the true rainfall. Fortunately, U. S. Weather Bureau raingages and observing procedures have been used at the stations selected in Areas A and B. However, some of the gages in these areas had been relocated and their reading interval altered during periods of record. Hence a small amount of station selection has been necessary in order to eliminate factors potentially introducing spurious rainfall differences.

The five criteria used for station selection were: 1) the station rainfall record should cover a period of at least 27 years; 2) it should begin not earlier than 1910; 3) it should end not earlier than 1959; 4) the reading of individual gages should be at reasonably constant intervals; and 5) the station location should remain relatively unchanged.

The lower limit of 27 years and the date of 1959 were rather arbitrarily chosen to reduce the work involved and yet cover a large fraction of the period of major increase in sugarcane production. The year 1905 marks the beginning of the official U. S. Weather Bureau surveillance of the gages among the islands.

FIG. 3. Same as Fig. 2 except for Maui in test area B.

The raingage stations selected were read at widely different intervals. Long-term trends should be revealed equally well by consistent daily or monthly readings (for example), but it is important that no systematic change be made in the reading interval during the period of record of each station. Records from stations with such altered reading intervals were partially or wholly discarded (e.g., station 449 on Maui).

Data discontinuities due to large or unknown relocations of gages have been avoided by discarding the records from these stations or by separate consideration of the rainfall at each location (e.g., station 221 on Hawaii where only 30 years of a 60-year record could be used). Relocation distances of 50–100 m were generally ignored. Special attention was given to moves made in a direction normal to isohyetal lines in regions of marked change in rainfall amounts (e.g., the region of station 192.2, Fig. 2).

4. Methods

No effort was made in this study to select rainfall records for specific time intervals of each year, as

Warner had done. He found selection necessary because of the short harvesting season, the unsteadiness of the winds, and the irregularity of shower rainfall occurrence in Queensland. In Hawaii these problems are minimal because harvesting is an almost year-round activity, the islands are in the relatively steady Pacific northeast trade-wind system, and showers are very common.

For each station the rank correlation of the annual rainfall with time was calculated (Suzuki, 1968). The annual rainfall amounts for each station were replaced by their ranks, one for the year with the least rain, two for the next, etc. The years were ranked chronologically. The rank correlation is given by

$$r_s = 1 - \frac{6}{n(n^2 - 1)} \sum_{i=1}^n d_i^2,$$

where d_i is the difference between the ranks, and n the number of years of record. If there is no trend in the data, the rank correlation would be zero. For the sample sizes involved, tables of significance levels of the ordinary regression coefficient can be used to test whether

TABLE 1. Student t values for testing significance of rainfall slope for 27-year periods beginning at three 10-year intervals, for three methods of standardizing data. See text for details.

	Data standardization method		
	1	2	3
Period beginning 1910			
Coast	0.90	1.33	1.42
Hawaii	-1.14	-0.73	-0.82
Maui	-1.24	-1.06	-1.04
Pooled	-1.19	-0.82	-0.89
Difference	1.93	1.52	1.64
Period beginning 1920			
Coast	1.52	1.79	1.81
Hawaii	-0.82	-0.67	-0.74
Maui	-0.82	-0.79	-0.78
Pooled	-0.84	-0.72	-0.77
Difference	1.62	1.47	1.54
Period beginning 1930			
Coast	1.48	1.48	1.45
Hawaii	-0.97	-0.95	-0.98
Maui	-0.71	-0.66	-0.71
Pooled	-0.92	-0.89	-0.92
Difference	1.61	1.45	1.48
Two-tailed significance levels			
Level	t		
10%	1.68		
5%	2.02		
2%	2.41		
1%	2.69		

r_s is significantly different from zero. Equivalently, r_s can be transformed to a t statistic,

$$t = r_s \left(\frac{n-2}{1-r_s^2} \right)^{\frac{1}{2}},$$

which has $n-2$ degrees of freedom. For large n the significant levels of the t statistic can be approximated by the levels obtained from the standard normal distribution. This gives a *rainfall trend index* for each station similar to the index used by Suzuki. For the sample sizes used in this study, a value greater than 2.0 or less than -2.0 would be required for statistical significance at the 5% level for any station considered individually. Since 76 stations are used in this study, the *trend index* value for statistical significance should be *increased*, but the exact value cannot be determined because of statistical correlation between stations.

Figs. 1, 2 and 3 show the trend index for each station for the three regions studied. The only stations which appear to have a significant trend are the coastal stations on the northwesternmost islands, Kauai and Oahu. These stations show an upward trend. Station 907 on Oahu, which shows a slight downward trend which is not significant, has a shorter record length than the other stations.

The next step in the analysis was a test for trends within entire regions instead of station by station. It

is obvious from the isohyetal lines on Figs. 2 and 3 that annual rainfall amounts at various sampling stations in our test areas vary greatly.

Standardization of the stations⁵ was necessary before combining the rainfall from different stations in a region. The mean, variance, skewness and kurtosis were estimated for both the total annual rainfall and the logarithm of the total annual rainfall at each station. As expected, the means for both the rainfall and the logarithms varied greatly from station to station. The log transformation tended to stabilize the variances. Because of the number of stations being combined, the skewness and kurtosis were not considered to deviate significantly from normality for either the rainfall or its logarithm.

The basic assumptions behind the statistical analysis are that the data combined from a group of stations are approximately normally distributed and that the deviations from any trend that may exist are uncorrelated for different years. The rainfalls for different stations during the same year are, of course, correlated but the analysis is not affected by this correlation since the stations are combined before the statistical analysis.

Three different methods of combining the stations of a region were tried. In the first method, 1, the annual rainfall amounts from each station were normalized by subtracting the station mean and dividing by the station standard deviation. The results for each year were then averaged over the stations in the region. The second method, 2, used the logarithms of the annual rainfall and subtracted the mean of the logarithm for each station before averaging over the stations. Because the length of record for each station was not the same, if a trend did exist, subtracting the sample mean from each station would tend to reduce the slope of the trend. The third method, 3, selected an origin of time in the center of the period of record and fit a straight line to the logarithm of the annual rainfall for each station. The station was then standardized by subtracting the intercept of this line from the logarithm of the rainfall axis before averaging over stations.

A linear trend in time was fitted to the data obtained by the three methods. A weighted least-squares analysis was used, the weight for a given year being the number of stations entering into the average. The slope of the line was then tested to see if it was significantly different from zero. The resulting t values are shown in Table 1 for the three methods of combining the stations, three different starting years, and the various regions. The *pooled* data is Hawaii and Maui Areas A and B pooled, and the *difference* is the standardized windward coastal data minus the pooled data. The coastal stations tend to have a positive slope and the Hawaii and Maui stations a negative slope, but none is significant above the 5% level.

⁵ Copies of the computer print-out sheets of station annual rainfall will be sent upon request.

5. Discussion, comments and speculations

We have considered other problems inherent in a study of secular trends in rainfall (WMO, 1966). One of these concerns trend-inhomogeneities not necessarily related to the problem being investigated. For instance, in and near Area A before the period of record, extensive conversion of forests to sugarcane fields and cattle grazing areas occurred. Associated with these changes and extending into the period of record has been the increasing use of internal combustion engines in agricultural operations and in transport. Fuels used in these engines are known to produce cloud condensation nuclei (Squires, personal communication). A major highway lies parallel to the coast and passes through the cane-growing regions of Area A (Fig. 1). Thus, during the period of record, other changes potentially influencing rainfall occurred, in addition to the increasing production of sugarcane.

These trend-inhomogeneities did not occur on Maui, however, where most of Area B and the regions windward of the area were forested during the period of record. Thus, agricultural practices produced many cloud nuclei over Area A, but not over Area B. In this case Warner's hypothesis led us to expect a relative downward trend of rainfall on Hawaii. Actually, the slight trend observed is down in Areas A and B, with a tendency toward a grouping of the stations showing the highest index numbers on Maui.

Sadler (personal communication) has suggested that winds associated with the well-known lee eddy in the saddle area of Maui (Leopold, 1949a, b) might carry smoke from the sugarcane fields (Fig. 1) over Area B, thus possibly affecting the clouds and rainfall there. While this seemed unlikely because of the direction of the prevailing surface winds of Area B (Leopold, 1949a), the idea was tested by determining the rainfall trends of the eastern one-half of Area B as opposed to the western portion. It was reasoned that cane-fire smoke would be more likely to influence the nearer western portion of the test area than the eastern part. However, the mean rainfall trends in each section were found to be about the same.

It may be useful to point out possible significant differences between the rainfall test regions of Queensland and Hawaii. Most of the Queensland raingages are much farther downwind from the cane-growing areas than are those of Hawaii (compare Warner's Fig. 1 to our Fig. 2). The greater distance probably assures more uniform average distribution of the smoke particles in Queensland than is possible in the shorter distances in Hawaii. Also, the burning rate is higher in Australia, due to the concentration of harvesting in a 3-month period. In Hawaii harvesting extends over about 11 months of the year and proceeds regardless of the weather. We estimate a potential total of one acre of harvest burning per square mile of cane-growing area per day. We don't know what fraction of this

area is actually burned. Warner estimates a total harvest burn of about 3 acres $\text{mi}^{-2} \text{ day}^{-1}$ in Queensland. Thus, it seems reasonable to expect that the Hawaii clouds would be less affected than those of Queensland by local cane-fire sources of cloud nuclei.

Upward trends in the windward coastal rainfall amounts on Kauai and Oahu may result from climatological changes toward more general rains. Can this be due to a reduction in the effectiveness of the Pacific high cell and an increase in windward coastal rainfall due to more cyclonic disturbances? Yeh *et al.* (1951) have suggested a trend toward an increase in the frequency of occurrence of "cyclonic situations" in Hawaii between 1916 and 1940. Worthley (1967) failed, however, to find any increase in frequency of frontal passages during the years 1936-66.

6. Conclusions

There is no indication that the slight downward trend in rainfall on Hawaii is due to cane-fire smoke from the harvesting operations of the increasingly productive sugar industry of the islands.

This rainfall study cannot, of course, be regarded as support for Warner's suggestion of a cane-fire effect on rainfall amounts. However, the results do not necessarily conflict with his results or with the finding (Warner and Twomey, 1967) that increased numbers of cloud nuclei in the atmosphere increase the stability of clouds and may, as a result, increase the time required for the completion of the raindrop growth processes.

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