Observation of Evaporation by Unconventional Methods in Hawaii: Small Cans and Piche Evaporimeters

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Abstract

A comparison among can, class-A pan and Piche evaporations and Penman PE (Eo, Et) based on half-day and daily data in Honolulu, Hawaii, shows that a can is a reliable estimator of class-A pan evaporation and Penman PE, while the relationship of Piche evaporation with pan evaporation and Penman PE gives lower correlation coefficients and larger standard errors of estimate. The Piche evaporimeter has some inherent ambiguities and inconsistencies and therefore is less reliable than cans for the field use. Mineral oil was found the most efficient in controlling evaporation from rain cans, although even the use of 5 mm thickness of oil did not completely stop evaporation on windy days.

1. Introduction

The advance of techniques to estimate potential evaporation and evapotranspiration has been made in the theoretical treatment of turbulent diffusion processes and the disposition of net radiation, whereas for the delineation of the distribution of evapotranspiration on a regional or national scale it is often the case that we still have to resort to the application of empirical formulas.

The accumulated literature, however, shows that even the most widely accepted Thornthwaite method proved unreliable in its application in tropical, hot continental, arid and polar environments (e.g., Chang 1959, p. 25; Pelton et al. 1960, pp. 389–393; Sibbons 1962, pp. 284–285; Chang 1965, p. 146). Noguchi (1986, pp. 171–178) further showed that the method gives a large seasonal discrepancies from observed pan evaporation even in the mid-latitude temperate environment of Japan, with monthly deviations in the range between −37.3 mm (underestimation) in March and +39.2 mm (overestimation) in July and the annual total absolute deviation reaching 300 mm as an average of 14 stations for 12 years.

In Honolulu, Hawaii, the Thornthwaite PE based on the monthly temperature data for 11 years (NOAA, 1965–1975) underestimated pan evaporation in all months, with the 11-year mean underestimation of 33% (63 mm/month) and the annual mean total underestimation of 752 mm. In terms of the monthly average, the largest deviation occurred in March with 43% (73 mm) underestimation and the smallest deviation in October (25% or 49 mm) and November (24% or 36 mm).

After the correction by a simple linear regression, the Thornthwaite PE coincided well with pan evaporation for Honolulu. However, no single correction factor was found satisfactory for the application to the entire Hawaiian Islands under the diversified climatic conditions.

It has been pointed out that where neither expensive instrumentation nor the use of empirical methods is practical for a reliable observation or estimation of PE in the field, the observation of pan evaporation could be substituted as a reliable alternative method in many climatic conditions (e.g., Chang 1961, p. 213; Stanhill 1961, pp. 164–166; McIlroy and Angus 1964, pp. 214–216; Davies 1965, 24–25; Chen 1976, pp. 52–58). Ekern (1966a, pp. 388–389), in his observation of evapotranspiration from Bermudagrass sod planted in Wahiawa Low Humic Latosol in percolate and hydraulic lysimeters on the Island of Oahu, showed that, when soil moisture stress was small, the consumptive use of water by sod was essentially the same as class-A pan evaporation.

There are many situations, however, in which the use of a large evaporation pan is undesirable in the field observation, and smaller pans, cans or even other unconventional types of evaporimeters have to be considered for the estimation of pan evaporation or PE.

In this study, the validity of small cans and Piche evaporimeters was examined for the estimation of PE in the subtropical Hawaiian environment. Evaporation from a small can has been reported to be closely correlated with pan evaporation in various places of the world (Marston 1961, p. 659; Davis 1963, pp. 5712–5714; Sims and Jackson 1971, p. 340; Iruthayaraj and Morachan 1978, p. 96). Before the class-A pan became the official instrument of evaporation, the Piche evaporimeter had been used in France and her former colonies (e.g., French Polynesia in the Pacific), New Zealand and so on as a standard instrument to measure the evaporating potential of the atmosphere. It was popular among ecologists as a field instrument (e.g., MacHattie and McCormack 1961, pp. 316–317; Lawson and Jenik 1967, pp. 777–778) and its reliability was discussed by Stanhill (1961, pp. 164–165). The instrument has recently rearoused considerable attention (Stigter et al. 1984, p. 193) and the recent introduction of similar evaporimeters which also use filter paper as an evaporating surface (Iwanami et al. 1978; Williams et al. 1984; Jacobs et al. 1986) may be construed to reflect the practical needs for handy evaporimeters for the field use.

The specific aims of this study were, therefore, (1) to examine the reliability of cans for measuring evaporation in the field by comparing a) the evaporation from four types of cans (black and white, with and without a screen) with each other, b) can evaporation with evaporation from the standard class-A pan and c) can evaporation with the estimated Penman PE from open water (or Eo) and Penman PE (or Et); and (2) to determine the reliability of Piche evaporimeters by comparing their readings with the pan data and the Penman PE.

2. Methods

The observation station was set up near the eastern end on the roof of the 4-storied engineering building (Holmes Hall) on the University of Hawaii campus (Fig. 1a and b) located in Manoa Valley in Honolulu on the leeward side of the Island of Oahu.

The university station was maintained from August 1978 until September 1979. Observations were regularly made twice a day around 0700 to 0800 HST and around 1800 to 1900 HST to determine the difference in behavior of can, class-A pan and Piche evaporations between day and night. On special days when the sky was almost clear, observations were made hourly to examine the diurnal change in can and pan evaporations and their relations to the vapor pressure gradient between the evaporating surface and the air.

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2.1 Can and Class-A Pan Evaporations

All cans used in this study were uniform in size, i.e., 153 mm in diameter, 170 mm in height and 3125 cm^3 in volume. Two cans were painted white both inside and outside and the other two black. Since all evaporation cans were intended to be used in the field and therefore had to be

(a)

(b)

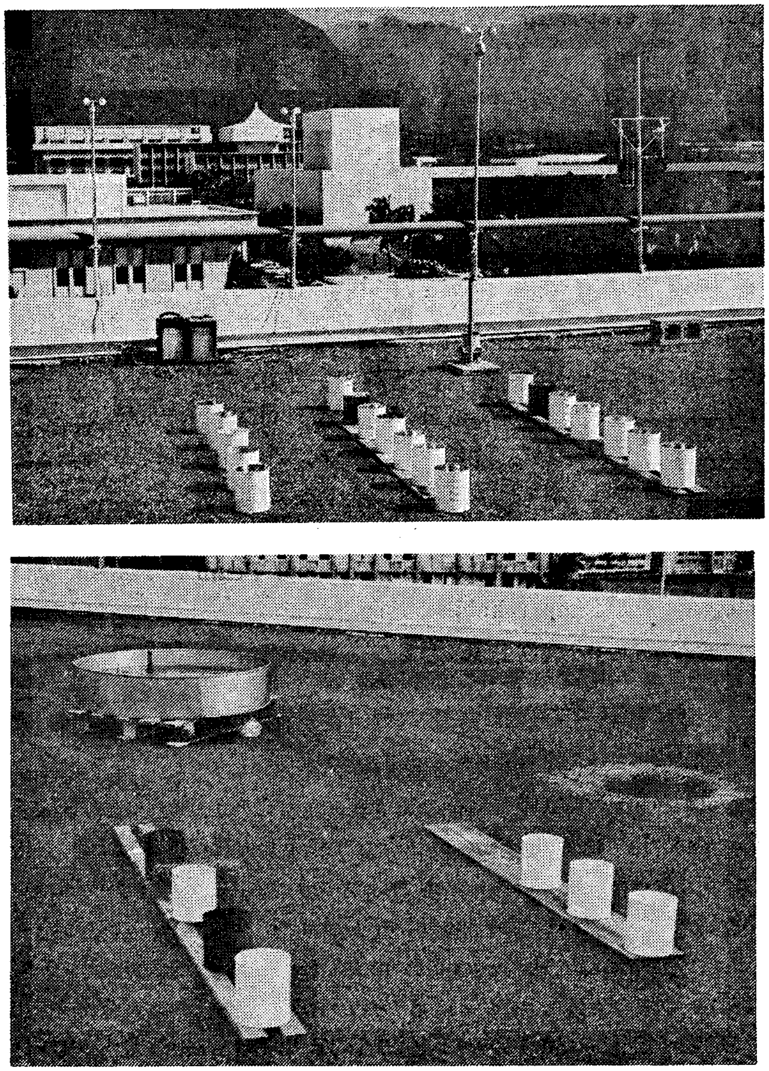

Fig. 1: Holmes Hall station on the University of Hawaii campus. (a) Observation of evaporation from cans and Piche evaporimeters (far right on the railing). (b) Observation of evaporation from cans and a class A pan.

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covered with a screen to ward off birds and other animals, the suppressing effect of screening of cans on evaporation was also examined at the university station. The screen consisted of wire netting of 2.5 cm hexagonal meshes, locally called a chicken net (hereafter referred to as a "net").

Each can had a uniform 85 mm long, sharp-pointed plastic needle fixed at the center of the can (Fig. 2a). Evaporation from the can was

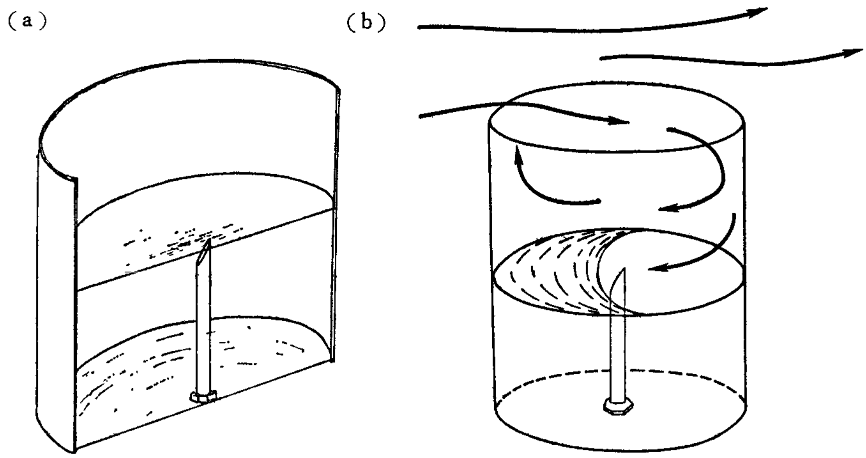

Fig. 2: Cans used for measuring evaporation and rainfall. (a) Cross-section of an evaporation can. (b) Rain can and typical opening in the oil film caused by the reverse wind.

obtained by measuring the amount of water required to refill the can up to the needle tip, thus keeping a constant level of water in the can. If there was rainfall during the past half a day, the evaporation was corrected by adding the amount of rainfall to the amount of the apparent evaporation:

Evaporation = water added + rainfall.

If the rainfall was heavy and the water level in the can was higher than the needle tip, water had to be removed from the can:

Evaporation = rainfall − water removed.

The U.S. Weather Bureau class-A pan is a standard, 121 cm diameter, 25.5 cm deep, galvanized iron pan that is unscreened and unpainted and mounted on a wooden open frame platform with its bottom 15 cm above the gravel-spread roof surface (Fig. 1b). The pan evaporation was measured by means of an ordinary hook gauge. The class-A pan was available in winter from November 1978 through January 1979 and in summer from July 1979 through September 1979.

To suppress the development of algae in the cans and the class-A pan, a small amount of copper sulphate was applied at a regular interval.

Can evaporation was correlated with pan evaporation and Penman PE. Since the days of high rainfall have been reported to register abnormally high evaporation probably due to rain splash from pans (Davies 1965, p. 21), the correlations were calculated separately using two types of evaporation data: (1) evaporation data excluding rain days, and (2) all evaporation data including rain days.

2.2 Rainfall and Oils

There are at least two practical requirements for the measurement of rainfall for the correction of observed pan or can evaporation, if the number of field stations are more than just a few and they are visited only once or twice a week: (1) economical instruments substituting for official rain gauges, and (2) suppression of evaporation from these instruments for the period between the two successive visits to the sites.

Rainfall was measured at the university station using cans of the same size as the ones used for measuring evaporation. The rain cans were painted white both inside and outside to decrease the thermal effect from the side walls of the cans and to reduce rusting. Three types of oil, i.e., vegetable oil, mineral oil and insulating oil, in five different thicknesses (1–5 mm) were used to examine the effectiveness of suppressing evaporation from the rain cans.

Vegetable oil is ordinary soybean oil. Mineral oil is available at drug stores as laxative. Insulating oil is used in high-voltage electrical transformers as an insulator, and 2 gals were provided for this study by the Hawaiian Electric Company by courtesy. Hamilton and Andrews (1953, p. 203) reported that insulating oil is effective as an inhibitor of evaporation from rain gauges.

Evaporation from the rain cans was checked in the same way as from the evaporation cans with plastic needles fixed at the center of the cans (Fig. 2b). To reduce possible splashing out of rainfall from the cans in heavy rains, the plastic needles were kept much shorter than the ones used in the evaporation cans. The amount of rainfall was determined by extracting only water from below the oil film using a plastic bottle with a narrow tube attached to the cap.

2.3 Piche Evaporation

The Piche evaporimeter is a graduated glass tube with one end closed. The flat open end is covered with a circular piece of filter paper pressed against it by a metal clip.

Two types of Piche evaporimeters were exposed at 1.5 m above the roof surface of the Holmes Hall building (Fig. 1a) and the accuracy for estimating PE was examined.

One type had a brass ring clip to hold a paper disk. The evaporating surface of a paper disk for this type of Piche was calculated as follows:

Evaporating surface = total surface area of a paper disk (upper and lower surfaces) − cross-sectional area of a glass tube = $2 \times 706.5\ mm^2 - 153.86\ mm^2 = 1259.14\ mm^2 = 12.59\ cm^2$.

The other type had a brass disk clip instead of a ring clip. This evaporimeter had a smaller evaporating surface because the brass disk covers a larger portion of the lower side of a paper filter:

Evaporating surface = $2 \times 706.5\ mm^2 - 2 \times 153.86\ mm^2 = 11.05\ cm^2$.

The total amount of Piche evaporation in rainfall equivalent was calculated as:

Evaporation (mm) = (Piche reading/evaporating surface area) $\times$ 10

Piche originally suggested that a pinhole should be perforated at the center of the paper disk to allow the entry of air to replace the evaporating water (Prescott and Stirk 1951, p. 245). This was done in the present study. Observations were made twice a day at the routine observation time. Daily Piche evaporation was compared with pan evaporation and Penman PE. Since the Piche evaporimeters have been reported to be too sensitive to wind (WMO 1971, p. 3), the relationships with the wind and the aerodynamic term of the Penman equation were also examined.

3. Results and Discussion

Various relationships among can, Piche and class-A pan evaporations and Penman PE and the effectiveness of oil to suppress evaporation from rain cans are explained in the following order:

3.1 Can evaporation
3.2 Can evaporation vs. pan evaporation
3.3 Pan evaporation vs. Penman PE
3.4 Can evaporation vs. Penman PE
3.5 Rainfall and oils
3.6 Piche evaporation vs. pan evaporation and Penman PE

3.1 Can Evaporation

Table 1 shows the relationship among evaporations from four types of cans, i.e., white can (net), white can (without a net), black can (net) and black can (without a net), for three different types of data:

Table 1 Linear relationships in evaporation among four types of cans, Holmes Hall, University of Hawaii.

Type of Data	y	a	b	x	r	Syx	n
(1) Half day, no-rain days only	(a) White (net)	−0.023	0.916	White	0.992	0.369	404
	(b) White (net)	0.309	0.756	Black (net)	0.989	0.425	401
	(c) White	0.373	0.744	Black	0.990	0.454	374
	(d) Black (net)	−0.045	0.913	Black	0.995	0.378	352
(2) Daily, no-rain days only	(e) White (net)	0.180	0.895	White	0.985	0.423	168
	(f) White (net)	−0.659	0.880	Black (net)	0.980	0.491	168
	(g) White	−0.889	0.887	Black	0.979	0.529	152
	(h) Black (net)	0.078	0.902	Black	0.985	0.463	146
(3) Daily, all days	(i) White (net)	0.280	0.885	White	0.980	0.454	268
	(j) White (net)	−0.553	0.870	Black (net)	0.978	0.491	262

(1) rainless half day data, (2) rainless daily data and (3) daily data under all weather conditions.

The first data type shows that: (1) The relationship between the white can (net) and white can (without a net) evaporations and the one between the black can (net) and black can (without a net) evaporations are almost identical in terms of the slope and y intercept of regression lines. The effect of a net on evaporation is about 10% for both white and black cans. (2) The relationship between the white and black can (both with a net) evaporations and the one between white and black can (both without a net) evaporations are also similar. (3) On the day when black can evaporation is around 10 mm/day, a representative value for a sunny day, the black can evaporation is 23 to 25% greater than the white can evaporation both with and without a net.

The second data type shows the relationship similar to the one based on the first data type. In other words, the first and the second data sets are almost identical in terms of the effect of a net on evaporation and the difference in evaporation between black and white cans. The inclusion of rainy days (third data type) changed the regression coefficients and correlation coefficients only slightly.

The high values of correlation coefficients and the consistency in the regression coefficients (a, b) in each particular relationship in all data types, (1) through (3), show that the can evaporation is consistent and reliable. If a high correlation and a small standard error of estimate are obtained in the relationship between can evaporation and pan evaporation or between can evaporation and Penman PE, it would follow that can evaporation is a reliable measure of PE.

The difference in daily evaporation between black and white cans was not related at all to global radiation at the university station ($r = -0.094$, $n = 43$, no-rain days only).

3.2 Can Evaporation vs. Pan Evaporation

The daily mean pan evaporation for the pan observation period (November 1978-January 1979, July-September 1979) was 6.7 mm for rainless days. A high value of pan evaporation in Hawaii was also pointed out elsewhere (Ekern 1966b, p. 431), and was explained by the persistent high elevation of the sun and low heating coefficient under the Hawaii environment (Ekern 1965, pp. 787–790).

The relationships between pan evaporation and can evaporation for various types of data, (1) through (5), are shown in Table 2. Some characteristic features are as follows:

a) Consistently high correlation coefficients between pan evaporation and the evaporation from four types of cans were obtained for all data types.

b) The relationship between can and pan evaporations based on the

Table 2 Linear relationships between class-A pan and can evaporations, Holmes Hall, University of Hawaii.

Type of Data	y	a	b	x	r	Syx	n
(1) Half day	(a) Pan	0.579	0.687	White (net)	0.822	0.826	88
(daytime only),	(b) Pan	0.521	0.632	White	0.849	0.769	69
no-rain days	(c) Pan	−0.071	0.609	Black (net)	0.800	0.919	72
only	(d) Pan	−0.434	0.588	Black	0.872	0.736	73
(2) Half day	(e) Pan	0.500	0.691	White (net)	0.933	0.703	154
(day & night),	(f) Pan	0.491	0.623	White	0.932		121
no-rain days	(g) Pan	0.732	0.514	Black (net)	0.915	0.773	126
only	(h) Pan	0.611	0.476	Black	0.936		132
(3) Half day	(i) Pan	0.469	0.697	White (net)	0.929	0.685	184
(day & night),	(j) Pan	0.460	0.628	White	0.929	0.686	150
rain≦10mm	(k) Pan	0.767	0.512	Black (net)	0.911	0.749	149
	(l) Pan	0.634	0.474	Black	0.934	0.658	162
(4) Daily,	(m) Pan	0.343	0.760	White (net)	0.915	0.713	56
no-rain days	(n) Pan	0.748	0.649	White	0.865	0.796	44
only	(o) Pan	−0.809	0.734	Black (net)	0.889	0.826	48
	(p) Pan	—	—	Black	—	—	—
(5) Daily,	(q) Pan	0.466	0.741	White (net)	0.890	0.800	84
rain≦15mm	(r) Pan	0.834	0.634	White	0.870	0.805	70
	(s) Pan	−0.493	0.705	Black (net)	0.874	0.894	70
	(t) Pan	0.106	0.579	Black	0.856	0.883	75

rainless day data showed slightly higher correlation coefficients than the one under rainfall $\leqq$ 10 mm for half-day data and rainfall $\leqq$ 15 mm for daily data.

c) The highest values of correlation coefficients in daily evaporation are found in the relationships between pan evaporation and white can (net) evaporation in data types (4) and (5) (i.e., m and q) in Table 2. Some of these relationships (a, e, i, m and q in Table 2) are shown in scattergrams (Fig. 3).

Evaporation occurs from the water surface whenever there is a difference in vapor pressure between water and the air. When temperature of the evaporating surface rises, the kinetic energy of water molecules is raised, resulting in an increase of vapor pressure of water which in turn makes the pressure gradient larger between the water surface and the air, thus increasing the evaporation.

Figure 4 shows the diurnal distribution of air temperature and water tempearture of various cans and a class-A pan for two almost clear day situations (cloud cover of less than 30% for 24 hours). The large difference in amplitude and time lag in the diurnal distribution of water temperature among cans and a pan, particularly in the morning hours, suggests that there is a large range in evaporation from one type of can or pan to another in 24 hours.

Figure 5 shows the diurnal distribution in saturation deficit and vapor pressure gradient between the air and the evaporating surfaces of various cans and a class-A pan. None of the cans, i.e., white (net), black (net) or insulated can, correctly follow pan evaporation although the shapes of the curves are quite similar. All cans and a class-A pan have a negative vapor pressure gradient early in the morning of August 7, 1979, implying that condensation occurred. The black (net) can is the earliest starter for evaporation in the morning and reaches the highest of all cans around 1400 HST. The white (net) can also has a higher vapor pressure gradient than the pan in the morning. These two black (net) and white (net) cans show a little earlier peak in vapor pressure gradient than the pan. In the afternoon, however, water in these two cans cools much faster than the pan water which has a greater heat storage capacity. Thus, there is much delay in the decrease in vapor pressure gradient in the pan. The white (net) can had a magnitude of vapor pressure gradient almost identical to the pan although the can and the pan have a time lag of about an hour. The higher vapor pressure

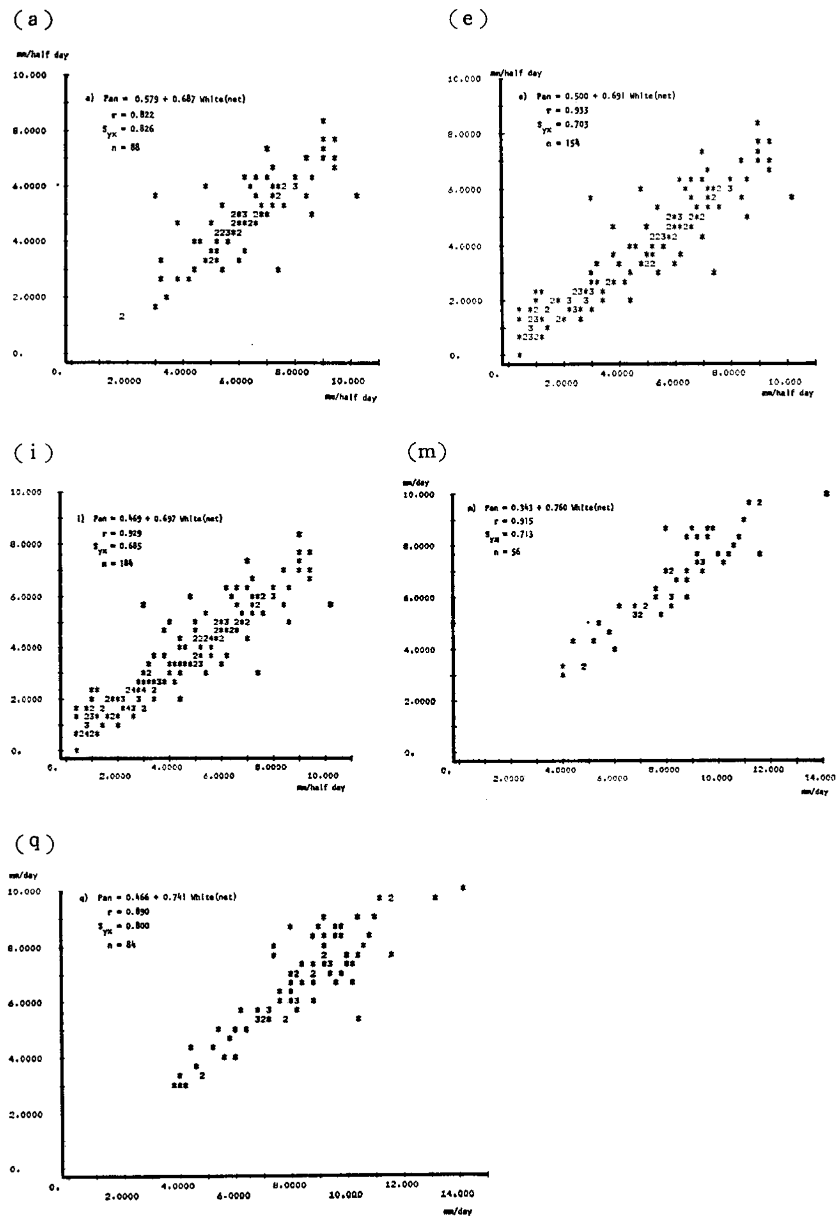

Fig. 3: Relationship between pan and can evaporations. (a) Pan vs. white can (net) evaporations based on half day (daytime only) data for no rain days only. (e) Pan vs. white can (net) evaporations based on half day (day and night) data for no rain days only. (i) Pan vs. white can (net) evaporations based on half day (day and night) data for days with rainfall ≦ 10 mm. (m) Pan vs. white can (net) evaporations based on daily data for no rain days only. (q) Pan vs. white can (net) evaporations based on daily data for days with rainfall ≦ 15 mm.

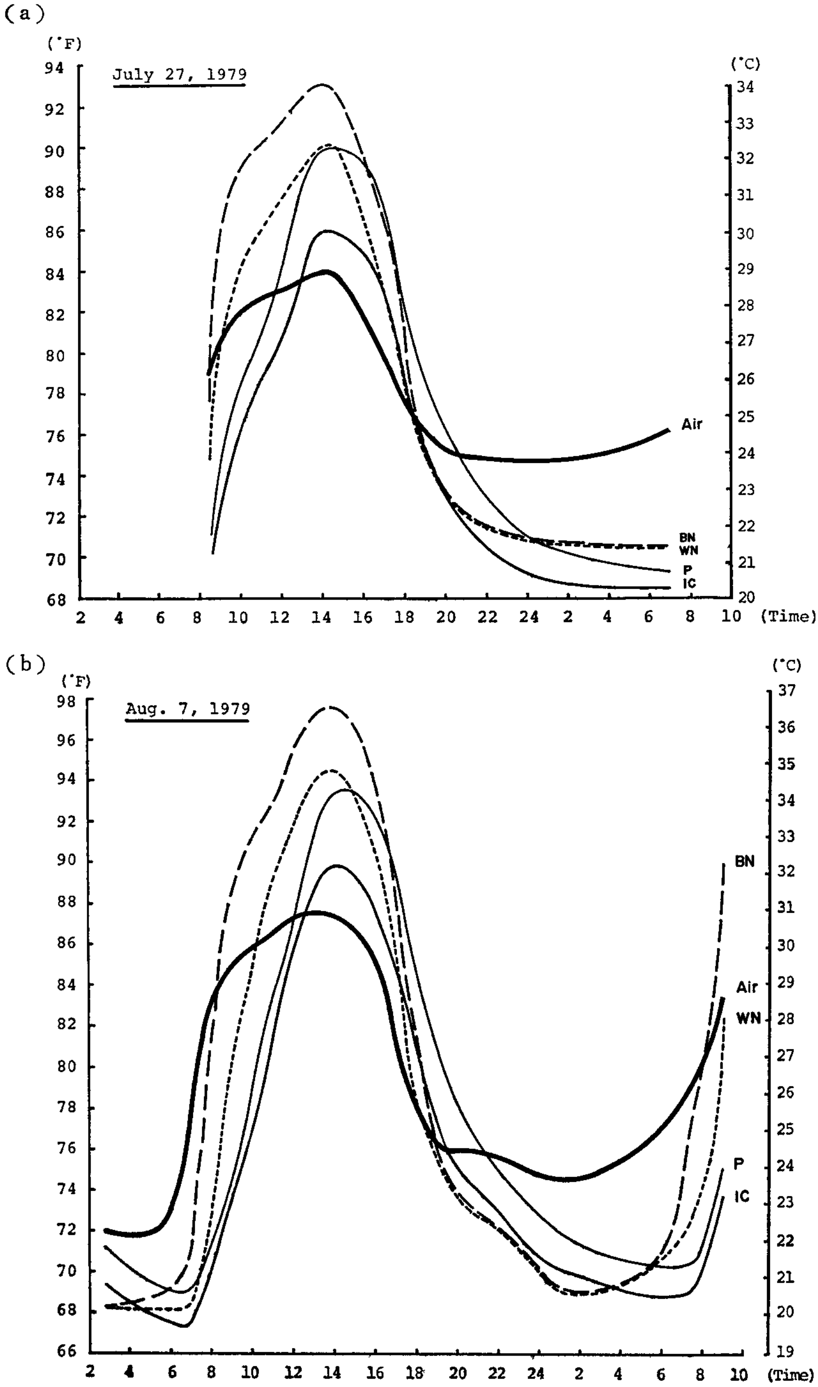

Fig. 4: Diurnal change in air temperature and water temperature of various cans and a class-A pan for two clear days, Holmes Hall, University of Hawaii.
Note: Air = air temperature, BN = black can (net), WN = white can (net), P = class-A pan, IC = insulated can.

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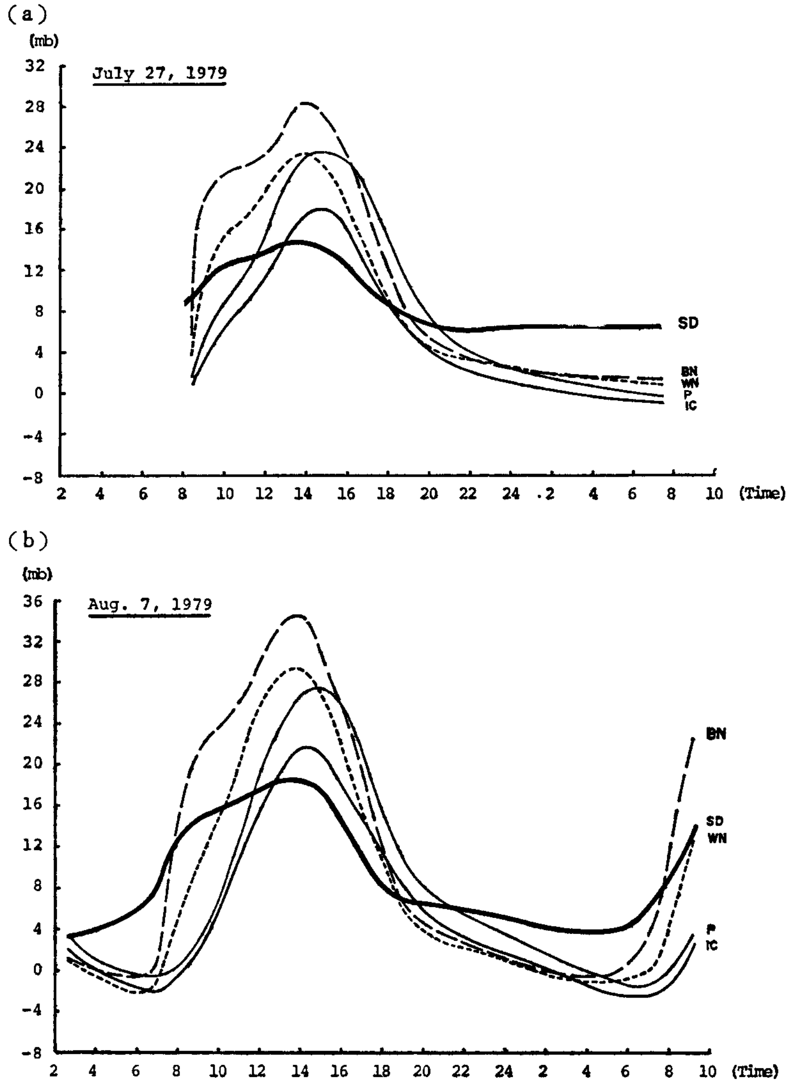

Fig. 5: Diurnal change in vapor pressure gradient between the evaporating surface and air for various cans and a class-A pan, Holmes Hall, University of Hawaii.
Note: SD = saturation deficit, BN = black can (net), WN = white can (net), P = class-A pan, IC = insulated can.

gradient of the pan, as compared to the cans, continues until around midnight. 一六〇

A can of the same size, insulated with 5 cm-thick freon-blown polyurethan foam (operated at the Holmes Hall station by Dr. Ekern of the WRRC, University of Hawaii) and painted white inside, indicated lower vapor pressure gradient than the pan for 24 hours, i.e., even in the morning and evening hours, although there is a good agreement in phase without any time lag between the pan and the insulated can.

The daily cycle of saturation deficit does not show much resemblance to that of the vapor pressure gradient of the pan, which means that the use of saturation deficit could lead to errors if used without knowing the characteristics of the diurnal change. For example, early in the morning when the vapor pressure gradient between the air and the evaporating surfaces of cans and a pan showed a negative value, the saturation deficit still remained positive, which was the major concern of Thornthwaite (1940, pp. 17–20) about the common but erroneous use of saturation deficit by field scientists.

The diurnal cycle of PE is diffeernt from any one of these pan or can evaporation cycles because water in a pan or a can stores heat and tends to reduce evaporation during the day but to favor it at night (Fig. 4). The Holmes Hall observation shows that on the average of 77-day pan evaporation (Nov.-Jan., and Aug.) 71% of daily pan evaporation occurred during the daytime with mean daytime evaporation of 4.6 mm and nighttime evaporation of 1.9 mm, while on the average of 240-day can (white, net) evaporation 76% of daily evaporation occurred during the daytime with mean daytime evaporation of 6.7 mm and nighttime evaporation of 2.1 mm. This difference between pan and can evaporation occurred due to the larger heat storage capacity of the pan water and its carryover to nighttime.

In Hong Kong, an average of about 82% of the daily pan evaporation occurred between 8:00 a.m. and 6:00 p.m. when the weather was fine and sunny, as against 56% when the weather was cloudy to overcast (Chen 1976, p. 9). All these facts imply that there is a slight carryover of evaporation from daytime to nighttime, although actual evapotranspiration is limited to daylight hours due to the stomatal closure in darkness except for some anomalous plants that have nocturnal opening and daytime closure of stomata (Penman 1963).

McIlroy and Angus (1964, pp. 212–213) compared the diurnal cycle of grass evaporation and water evaporation and showed that there is a significant time lag in peak evaporation between the two on a clear summer day. Nighttime water evaporation always remained positive despite the fact that net radiation became negative. Doorenbos and Pruit (1975, p. 50) also showed that daytime storage of heat within the pan can be appreciable and may cause almost equal distribution of evaporation between day and night, while most crops lose 95% or more of their 24-hour loss during daytime hours.

However, the discrepancy between the diurnal change in pan evaporation and that in PE will not cause a critical problem in the estimation of PE from the pan or can evaporation if the estimated PE is the mean of more than a couple of days.

Despite the fact that the white (net) can evaporation and pan evaporation had different daily patterns, a high correlation existed between them on a daily basis ($r = 0.915$, $n = 56$ for no-rain days; $r = 0.890$, $n = 84$ for days with rainfall $\leqq 15$ mm). Although the evaporation from the insulated can was not measured, a high correlation between pan and insulated can evaporations was also expected as indicated by Van Haveren and Farmer (1971).

3.3 Pan Evaporation vs. Penman PE (Eo, Et)

Both open water evaporation (Eo) and Et were calculated on a daily basis for the university station by the Penman method using albedos of 0.05 and 0.25, respectively. Table 3 shows the relationships between pan evaporation and Penman PE for three types of data: (1) no rain days only, (2) days with daily rainfall of less than 15 mm and (3) all days.

For all of the above three types of data, the relationship between pan evaporation and Penman PE showed high correlations, with the highest in data type (1) and the lowest in data type (3), suggesting a possible contribution of rainfall to the error in pan evaporation, as pointed out by Finkelstein (1961, p. 509) and Davies (1965, p. 21).

The assertion by Gilbert and van Bavel (1954) and confirmation by Chang (1961, p. 212) that the Penman method does not apply to periods

Table 3 Linear relationships between class-A pan evaporation and Penman PE, Holmes Hall, University of Hawaii.

Type of Data	y	a	b	x	r	Syx	n
(1) Daily, no-rain days only	(a) Pan	0.784	1.129	$PE_{a=0.05}$	0.906	0.783	56
	(b) Pan	0.965	1.375	$PE_{a=0.25}$	0.924		56
(2) Daily, rain≦15mm	(c) Pan	0.775	1.154	$PE_{a=0.05}$	0.856	0.973	86
	(d) Pan	0.772	1.443	$PE_{a=0.25}$	0.884		86
(3) Daily, all days	(e) Pan	1.499	1.030	$PE_{a=0.05}$	0.773		89
	(f) Pan	1.490	1.300	$PE_{a=0.25}$	0.799		89

Note: a = albedo; $PE_{a=0.05}$ = Eo; $PE_{a=0.25}$ = Et.

of less than 5 days were not reconfirmed in this study.

3.4 Can Evaporation vs. Penman PE (Eo, Et)

Daily Penman PE was also correlated with the daily can evaporation for the university station. Since the white (net) can evaporation seems to be a somewhat better estimator of pan evaporation, only the relationships between the Penman PE and the white (net) can evaporation are shown in Table 4, for two different types of data: (1) no-rain days only and (2) all days with rainy days inclusive. Scattergrams of these relations are given in Fig. 6.

All the above results are summarized in Figs. 7a and 7b, which show the relationships among pan evaporation, white (net) and black (net) can evaporations and the Penman PE for no-rain days (Fig. 7a) and all days with rainy days inclusive (Fig. 7b), respectively, on a daily basis. The increased correlation coefficients from Fig. 7b to Fig. 7a suggest that there would be a considerable improvement in all relationships if there is no rainfall.

3.5 Rainfall and Oils

The effectiveness of oil to suppress evaporation from cans used as substitutes of rain gauges was checked for as long as 125 days using three different types of oil in five different thicknesses (Fig. 8).

Vegetable oil showed the largest variation, with 1 mm of oil being the least effective and 5 mm of oil the most effective of all types of treatments. However, the oil was found to be the least attractive as an inhibitor of evaporation because it developed into a sticky jello-like layer 10 to 15 days after the application and partially solidified in 20 to

Table 4 Linear relationships between Penman PE and can evaporation, Holmes Hall, University of Hawaii.

Type of Data	y	a	b	x	r	Syx	n
(1) Daily, no-rain days only	(a) $PE_{a=0.05}$	0.749	0.607	White (net)	0.817		164
	White (net)	2.039	1.098	$PE_{a=0.05}$	0.817	1.295	164
	(b) $PE_{a=0.25}$	0.357	0.509	White (net)	0.840		164
	White (net)	0.034	1.386	$PE_{a=0.25}$	0.840	1.217	164
(2) Daily, all days	(c) $PE_{a=0.05}$	0.934	0.585	White (net)	0.776		266
	White (net)	2.583	1.001	$PE_{a=0.05}$	0.776	1.410	266
	(d) $PE_{a=0.25}$	0.564	0.486	White (net)	0.788		266
	White (net)	2.503	1.278	$PE_{a=0.25}$	0.788	1.350	266

Note: a = albedo; $PE_{a=0.05}$ = Eo; $PE_{a=0.25}$ = Et.

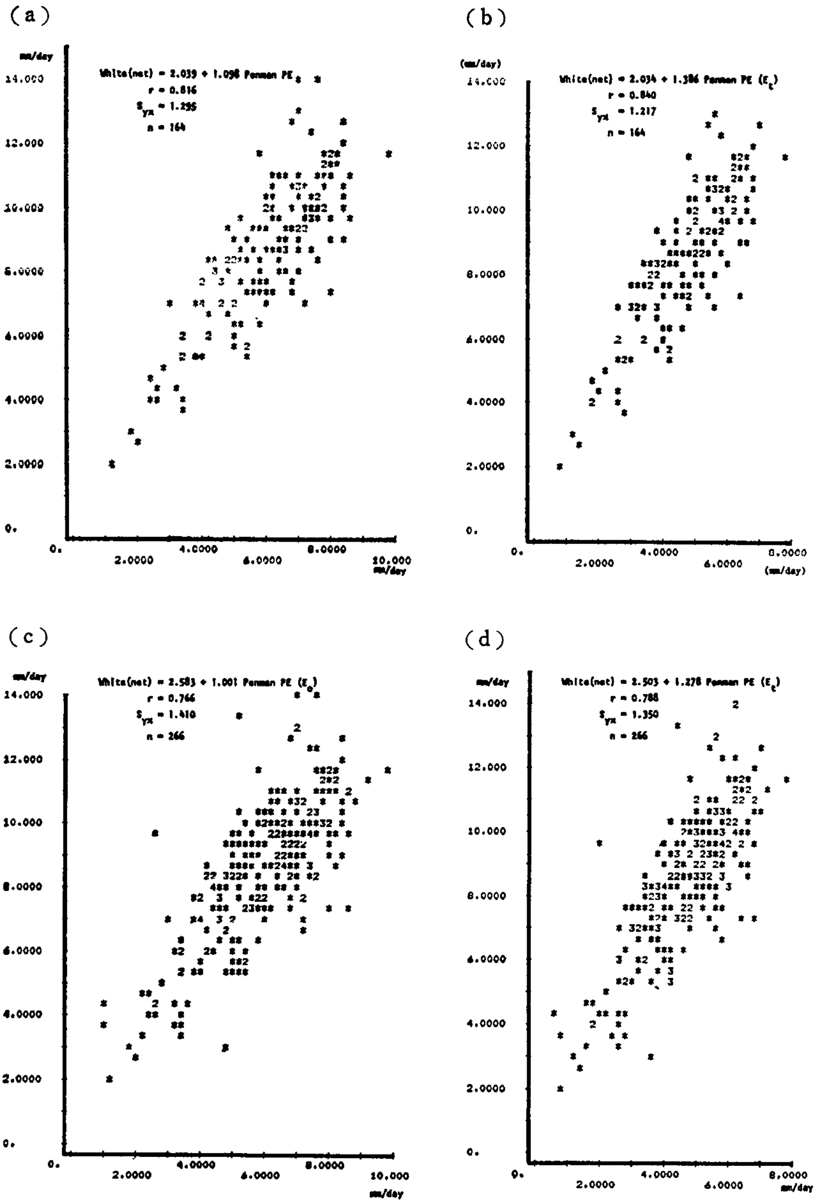

Fig. 6: Relationship between can evaporation and Penman PE.
(a) White can (net vs. Penman PE (Eo) based on daily data for no rain days only. (b) White can (net) vs. Penman PE (Et) based on daily data for no rain days only. (c) White can (net) vs. Penman PE (Eo) based on all daily data. (d) White can (net) vs. Penman PE (Et) based on all daily data.

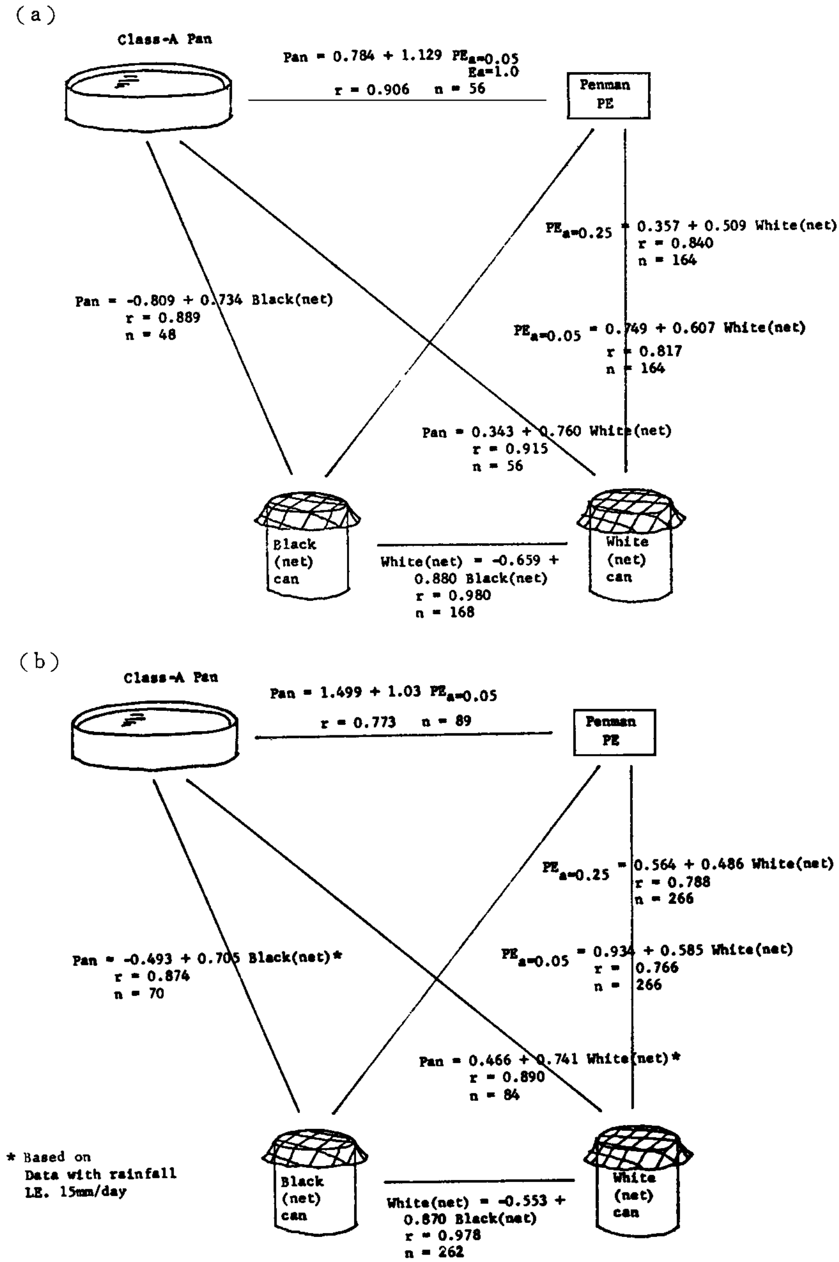

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Fig. 7: Summary of relationships among can and class-A pan evaporations and Penman PE (Eo, Et), Holmes Hall station, University of Hawaii.
(a) Relationships based on daily data for no rain days only.
(b) Relationships based on all daily data.

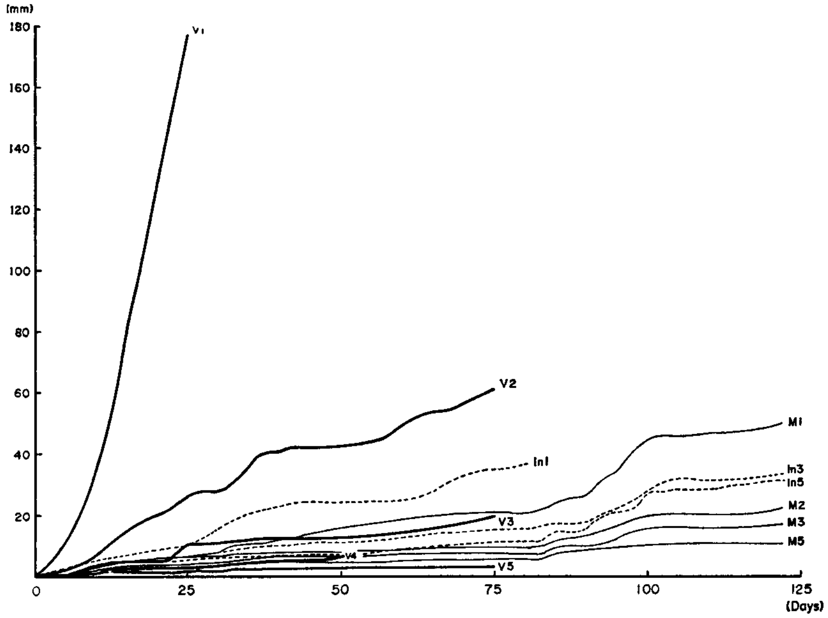

Fig. 8: Cumulative change in evaporation from rain cans using different thicknesses of three types of oil, Holmes Hall, University of Hawaii. Note: V, M and In stand for vegetable oil, mineral oil and insulating oil, respectively. The number indicates the thickness of oil (e.g., M5 = 5 mm-thick mineral oil).

25 days, finally damaging the rain can. This reaction of vegetable oil always started in the can with the thinnest oil of 1 mm, but soon spread to all cans.

Mineral oil and insulating oil of different thicknesses showed much smaller variation in their efficiency to control evaporation. However, even the use of 5 mm-thick oil did not completely stop evaporation. The overall superiority of mineral oil over insulating oil is evident. Fig. 8 and Table 5 show that with the use of 5 mm thickness of mineral oil, the cumulative evaporation would be 2.5–4.1 mm/month. On a calm day, even 1 mm thickness of oil effectively stopped evaporation, whereas if the wind was stronger, the oil layer was moved to the windward side of the can by the return air current which rebounded at the inner leeward wall of the can, thus exposing the water surface for evaporation (Fig. 2b). Hamilton and Andrews (1953, p. 204) reported that the use of insulating oil of 3.8 mm thickness almost indefinitely stopped evaporation from the 8-inch rain gauge without a funnel. Our experiment showed, however, that a significantly deeper oil layer had to be used to effectively control evaporation from the type of rain can used in this study.

Table 5 Relationship between different thicknesses of three types of oil and evaporation from rain cans. Holmes Hall, University of Hawaii.

Elapsed Time (days)	Cumulative Evaporation (mm)								
	VO 1	VO 3	VO 5	MO 1	MO 3	MO 5	IO 1	IO 3	IO 5
.5	0.5	0.4	0.0	0.2	0.2	0.7	1.7	1.6	1.6
5	10.2	1.5	0.5	1.3	1.0	1.7	2.7	3.2	2.7
10	33.7	3.5	1.0	3.2	1.6	2.5	5.1	4.2	3.7
15	78.1	4.9	1.4	4.6	3.4	3.6	6.9	5.5	5.2
20	126.0	4.9	1.4	5.8	3.5	3.8	8.9	5.7	5.2
25	177.4	10.2	1.7	6.4	3.5	3.8	9.7	5.7	5.2
30	191.5	10.8	1.7	7.8	4.1	4.1	15.9	7.3	6.0
35	202.9	11.5	2.4	10.6	5.4	4.3	20.5	9.4	6.5
40	240.1	12.1	2.4	12.0	6.3	4.3	22.5	10.1	6.8
45	254.6	12.4	2.7	14.1	6.3	4.5	24.1	11.3	7.1
50	262.8	12.8	2.9	15.8	6.3	4.5	24.1	11.3	7.1
55	277.2	13.3	2.9	17.0	6.6	4.5	24.2	11.4	7.4
60	305.6	14.1	2.9	18.6	7.1	4.9	24.5	12.8	8.8
65	331.6	15.8	2.9	19.8	7.2	5.4	27.7	14.0	9.5
70	356.7	17.8	2.9	20.5	7.4	5.4	32.9	14.7	10.4
75	—	—	—	20.7	7.4	5.4	34.9	15.5	11.3
80	—	—	—	20.9	7.4	5.4	37.0	15.5	11.3
85	—	—	—	24.0	9.5	7.3	78.9	17.5	14.7
90	—	—	—	26.4	10.0	8.3	—	17.6	15.5
95	—	—	—	34.5	12.2	9.0	—	21.2	21.5
100	—	—	—	44.4	12.5	10.4	—	26.2	27.5
105	—	—	—	45.9	15.8	10.6	—	31.1	28.1
110	—	—	—	46.6	15.8	10.6	—	31.1	28.1
115	—	—	—	47.3	16.0	10.8	—	31.7	39.8
120	—	—	—	48.7	16.8	10.8	—	32.6	31.1

Note 1: Underlines denote renewal of oil.
Note 2: VO, MO and IO stand for vegetable oil, mineral oil and insulating oil, respectively. The number following the oil type indicates the thickness of oil (e.g., MO5 = 5 mm-thick mineral oil).

Our experiment further showed that an oil of higher viscosity would reduce the effect of wind on the oil surface and hence evaporation. At the same time it was suspected that highly visous oil would slow the movement of raindrops through the oil layer to join the water body under the oil film, thus allowing evaporation on windy days.

3.6 Piche Evaporation vs. Pan Evaporation and Penman PE

A comparison of evaporation between the two types (ring-clip and disk-clip types) of Piche based on half-day evaporation data shows that both Piche types agreed with each other strikingly well if an appropriate

Table 6 Linear relationships between class-A pan and Piche evaporations, and between Penman PE (Eo, Et) and Piche evaporation, Holmes Hall station, University of Hawaii.

Type of Data	y	a	b	x	r	Syx	n
Pan vs. Piche							
(1) No-rain days only							
(a) Half day, daytime only	Pan	0.541	0.600	Piche 1	0.792	0.789	53
(b) Half day,	Pan	0.280	0.517	Piche 1	0.712	1.190	96
day & night	Pan	−0.203	0.608	Piche 2	0.753	1.164	40
(c) Daily	Pan	1.983	0.370	Piche 1	0.859	0.885	35
	Pan	1.972	0.380	Piche 1, 2	0.848	0.805	47
(2) Rain≦15mm							
(d) Daily	Pan	1.921	0.377	Piche 1	0.838	0.939	60
	Pan	1.972	0.380	Piche 1, 2	0.848	0.850	83
Penman PE vs. Piche							
(1) All days, daily	Eo	2.648	0.292	Piche 1	0.576	1.460	231
	Eo	2.451	0.344	Piche 2	0.660	1.315	193
	Eo	2.577	0.314	Piche 1, 2	0.609	1.405	424
	Et	1.884	0.253	Piche 1	0.620	1.126	231
	Et	1.884	0.265	Piche 1, 2	0.640	1.083	423
(2) Daily wind speed ≦2m/sec, daily	Eo	1.749	0.394	Piche 1, 2	0.638	1.213	86

Note: Both Piche 1 and 2 are the ring-clip type replicate instruments located in the same place at Holmes Hall, University of Hawaii.

area of the evaporating surface of a filter paper was used for each type of the instrument as mentioned above:

Disk-clip type = 0.167 +1.039 Ring-clip type

(r = 0.985; Syx = 0.461 mm; n = 258).

The Piche evaporimeter has been conventionally used in the screen and because of this practice, the ratio of pan evaporation to Piche evaporation has been reported to fluctuate widely from month to month (Prescott and Stirk 1951, p. 244). The relationships between pan and Piche evaporations and between Penman PE (Eo, Et) and Piche evaporation for the university station are given in Table 6. The relationships suggest that:

1. There is a high correlation between pan and Piche evaporations for both half-day and daily evaporation data and both with and without rain.

2. The relationship between Penman PE and Piche evaporation is not very impressive, however, with the correlation coefficient of 0.6.

It has been pointed out that the instrument is very sensitive to the wind (WMO 1971, p. 9). Stanhill (1962) showed that the weekly mean of Piche evaporation, measured in a standard screen at Gilat, Israel in the steppe climate, is highly correlated with the calculated Penman aerodynamic term ($r = 0.89$) and recommended a simplified form of Penman formula using the Piche evaporation data.

Fitzpatrick and Stern (1966, pp. 234–235) also found significant correlation (0.83) between the daily Piche evaporation and a similar aerodynamic term for western Australia. Heine (1981), on the other hand, found that the y intercepts of the Piche vs. aerodynamic term monthly regressions change systematically in New Zealand and fitted a polynomial curve to take account of the change, thus successfully relating daily Piche readings to the Penman aerodynamic term.

At the university station, however, neither wind speed (Fig. 9), nor Penman's aerodynamic term (Fig. 10), are, as a whole, closely

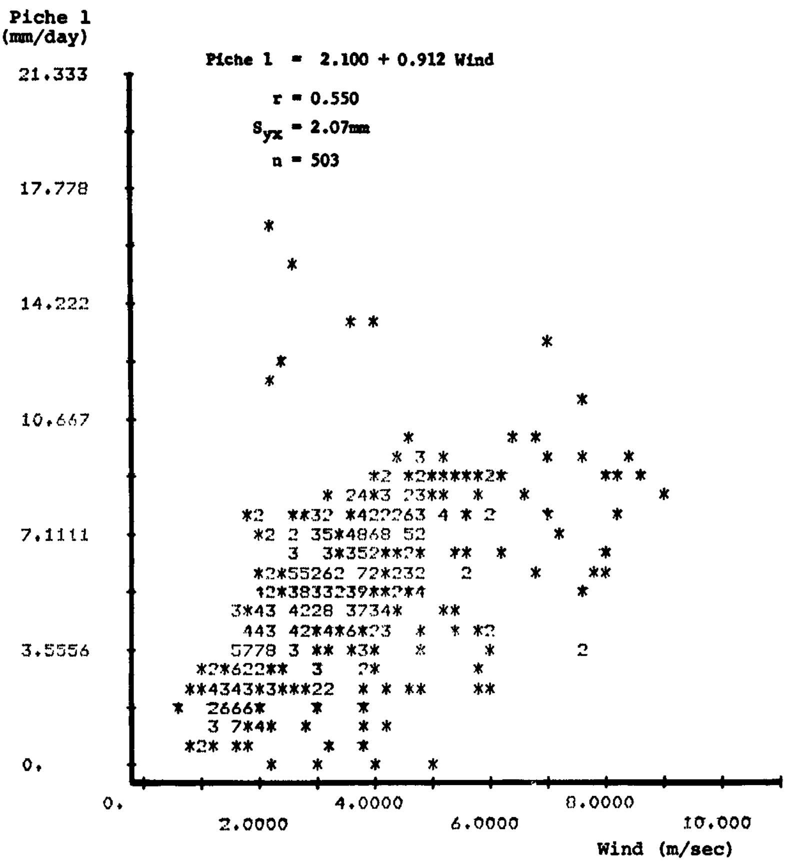

Fig. 9: Relationship between daily Piche evaporation and wind speed, Holmes Hall, University of Hawaii.

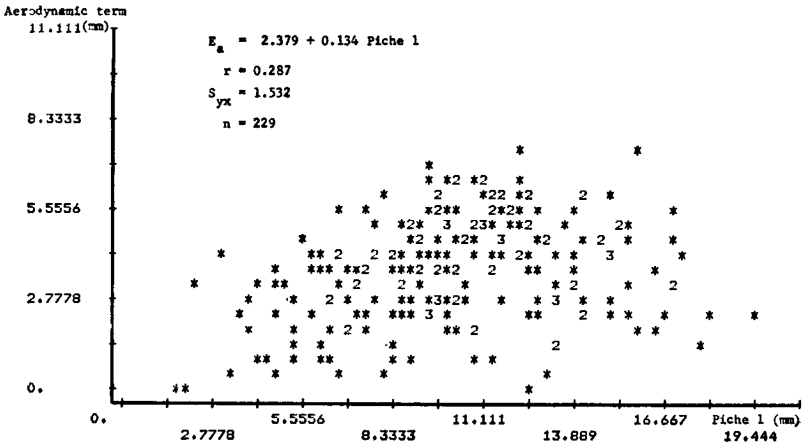

Fig. 10: Relationship between daily Piche evaporation and the aerodynamic term (Ea) of the Penman formula, Holmes Hall station, University of Hawaii.

correlated with the Piche evaporation on a daily basis. This may be partly because the Piche evaporimeters were exposed in the open at the university station and experienced more direct radiative effect, while in the observations by Stanhill (1962) and others the instrument was used in a louvered screen.

4. Conclusion

The validity of small cans and Piche evaporimeters as substitutes of class-A pans and estimators of Penman PE was examined in the Hawaiian environment and the following results were obtained:

1) The relationship among evaporations from four types of cans (black and white; with and without a net) was consistent with high correlation coefficients. The retarding effect of a net on evaporation was about 10%. Despite high correlation between black and white can evaporations, there was no significant correlation between the difference in these evaporations and global radiation.

2) Pan evaporation can be approximated by can evaporation reasonably well on both half day and daily bases. A comparison in vapor pressure gradient among various types of cans and a pan showed that each can or pan had its own phase and magnitude, which caused a difference in evaporation.

3) The relationship between daily pan evaporation and Penman PE

showed high correlation coefficients, although rainfall seemed to have contributed to the increase in errors in the relationship.

4) The relationship between daily can evaporation (white, net) and Penman PE was also highly significant, although the correlation again dropped with the inclusion of data for rain days.

5) The Piche evaporimeter was not found so sensitive to the wind in Hawaii as pointed out elsewhere. There was a high correlation between daily Piche and pan evaporations. However, the correlation between Piche and Penman PE was not striking. The correlation did not improve even by the use of data with daily wind speed $\leqq 2$ m/sec.

6) Mineral oil was found most efficient in suppressing evaporation from rain cans. However, even the use of 5 mm thickness of oil did not completely stop evaporation under windy conditions, although the same oil of less thickness was highly effective in calm weather conditions.

References:

Chang, J. H. 1959. An Evaluation of the 1948 Thornthwaite Classification. Ann. Ass. Amer. Geog., 49, 24–30.

Chang, J. H. 1961. Microclimate of Sugar Cane. Hawaiian Planters' Record, 56, 195–225.

Chang, J. H. 1965. On the Study of Evapotranspiration and Water Balance. Erdkunde, 19, 141–150.

Chen, T. Y. 1976. Evaporation and Evapotranspiration in Hong Kong. Tech. Note No. 42, Royal Observatory, Hong Kong. 67 p.

Davies, J. A. 1965. Evaporation and Evapotranspiration at Ibadan. Nigerian Geog. Jour., 8, 17–31.

Davis, J. R. 1962. Relationship of Can evaporation to Pan evaporation and Evapotranspiration. Jour. Geoph. Res., 68, 5711–5718.

Doorenbos, J. and Pruitt, W. O. 1975. Guidelines for Predicting Crop Water Requirements. Irrigation and Drainage Paper No. 24, FAO, Rome, 179 p.

Ekern, P. C. 1965. The Fraction of Sunlight Retained as Net Radiation in Hawaii. Jour. Geoph. Res., 70, 785–793.

Ekern, P. C. 1966a. Evapotranspiration by Bermudagrass Sod, *Cynodon dactylon* L. *Pers.*, in Hawaii. Agron. Jour., 56, 387–390.

Ekern, P. C. 1966b. Evaporation from Bare Low Humic Latosol in Hawaii. Jour. Appl. Met., 5, 431–435.

Finkelstein, J. 1961. Estimation of Open Water Evaporation in New Zealand. New Zealand Jour. Sci., 4, 506–522.

Fitzpatrick, E. A. and Stern, W. R. 1966. Estimates of Potential Evaporation Using Alternative Data in Penman's Formula. Agricul. Met., 3, 225–239.

Hamilton, E. L. and Andrews, L. A. 1953. Control of Evaporation from Rain Gages by Oil. Bull. Am. Met. Soc., 34, 202–204.

Heine, R. W. 1981. Comparison of Monthly Piche Readings with the Penman

Aerodynamic Term in the New Zealand Climate Network. Agricul. Met., 25, 67–74.

Iruthayaraj, M. R. and Morachan, Y. B. 1978. Relationship Between Evaporation from Different Evaporimeters and Meteorological Parameters. Agricul. Met., 19, 93–100.

Iwanami, Y., Hibino, K. and Iizumi, S. 1978. An Atmometer for Ecological Research. Nihon Seitai Gakkaishi, 28, 269–271.

Jacobs, A. F. G., Bink, N. J. and Williams, R. 1986. Evaporation Data from a Capillary Evaporimeter. Jour. Hydrol., 86, 85–92.

Lawson, G. W. and Jenik, J. 1967. Observations on Microclimate and Vegetation Interrelationships on the Accra Plains (Ghana). Jour. Ecol., 55, 773–785.

MacHattie, L. B. and McCormack, R. J. 1961. Forest Microclimate: A Topographic Study in Ontario. Jour. Ecol., 49, 301–323.

Marston, R. B. 1961. Substitution of Small Cans for Weather Bureau Pans in Measuring Evaporation. Jour. Geoph. Res., 66, 657–659.

McIlroy, I. C. and Angus, D. E. 1964. Grass, Water and Soil Evaporation at Aspendale. Agricul. Met., 1, 201–224.

Noguchi, Y. 1986. Application of Penman and Thornthwaite Methods and Water Balance in Japan. 165–182. In: Proceedings, 20th Anniversary of the Faculty of Letters, Kokushikan University, Tokyo (in Japanese).

Pelton, W. L., King, K. M. and Tanner, C. B. 1960. An Evaluation of the Thornthwaite and Mean Temperature Methods for Determining Potential Evapotranspiration. Agron. Jour., 52, 387–395.

Penman, H. L. 1963. Vegetation and Hydrology. Tech. Comm. 53, Commonwealth Bur. Soils. 124 p.

Prescott, J. A. and Stirk, G. B. 1951. Studies on the Piche Evaporimeter. Austra. Jour. Appl. Sci., 2, 243–256.

Sibbons, J. L. H. 1962. A Contribution to the Study of Potential Evapotranspiration. Geog. Ann., 44, 279–392.

Sims, J. R. and Jackson, G. D. 1971. Field Measurement of Pan Evaporation. Agron. Jour., 63, 339–340.

Stanhill, G. 1961. A Comparison of Methods of Calculating Potential Evapotranspiration from Climatic Data. Israel Jour. Agricul. Res., 11, 159–171.

Stanhill, G. 1962. The Use of the Piche Evaporimeter in the Calculation of Evaporation. Quart. J. R. Met. Soc., 88, 80–82.

Stigter, C. J., Uiso, C. B. S. and Rashidi, A. M. G. M. 1984. Evaporation Data from a Piche Evaporimeter—A Comment Using Tanzanian Results. Jour. Hydrol., 73, 193–198.

Thornthwaite, C. W. 1940. Atmospheric Moisture in Relation to Ecological Problems. Ecology, 21, 17–28.

van Haveren, B. P. and Farmer, E. E. 1971. An Insulated Evaporimeter. Water Resou. Bull., 7, 1250–1252.

Williams, R., Zangvil, A. and Karnieli, A. 1984. A Portable Evaporimeter for Rapid Measurement of the Evaporation Rate of Water. Agricul.

Forest Met., 32, 217–224.
WMO. 1971. Chapter 8: Measurement of Evaporation. In: Guide to Meteorological Instrument and Observing Practices. 4th ed., WMO No. 8, TP. 3.

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