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EVAPORIMETRY IN THE CANAL ZONE. PART II. COMPARISON OF VARIOUS TYPES OF EVAPORIMETERS ON AN HOURLY BASIS

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EVAPORIMETRY IN THE CANAL ZONE
PART II
COMPARISON OF VARIOUS TYPES OF EVAPORIMETERS ON AN HOURLY BASIS

TECHNICAL RESEARCH NOTE

BY
WILFRIED H. PORTIG

AUGUST 1972

UNITED STATES ARMY TROPIC TEST CENTER
FORT CLAYTON, CANAL ZONE

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13. ABSTRACT

The United States Army Tropic Test Center conducted a project in the Canal Zone entitled Environmental Data Base for Regional Studies in the Humid Tropics during the years 1965 through 1969. Evaporation was one of the parameters under investigation.

This report discusses instrumentation available for measuring evaporation and highlights serious deficiencies encountered. Measurements using the Standard Pan and Wild, Livingstone, and Piche evaporimeters were compared and discrepancies studied.

Evaporation loss was found to be greatly influenced by differences in measuring instruments used—location, elevation, size of blotting paper, sheltering, and amount of radiation.

It was concluded that different types of evaporimeters produce different measurements, and none has been adequately related to natural evaporation.

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This report discusses instrumentation available for measuring evaporation and highlights serious deficiencies encountered. Measurements using the Standard Pan and Wild, Livingstone, and Piche evaporimeters were compared and discrepancies studied.

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It was concluded that different types of evaporimeters produce different measurements, and none has been adequately related to natural evaporation.

FOREWORD

During the years 1965 through 1969 the United States Army Tropic Test Center conducted a project in the Canal Zone entitled "Environmental Data Base for Regional Studies in the Humid Tropics." It was sponsored by the Advanced Research Projects Agency and Army Research Office of the Office of the Chief of Research and Development. Among other parameters, evaporation was recorded. Analysis of these evaporation data has been published in two parts under the common title "Evaporimetry in the Canal Zone." This report is Part II.

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1. INTRODUCTION

Although evaporation is an important factor in natural processes, little precise quantitative information is available. All of the many techniques used to measure or compute evaporation from other parameters are deficient in one way or another. The choice of the method depends largely upon the intended use of the data. For example, interest can be focused on evaporation from a single body, from a population (of plants, animals, soils, or combinations thereof), from an area, from a region, from an ocean, at a certain moment, during a day, or in the course of a year. The complexity of these conditions is compounded by the unknown amount of water available for evaporation.

2. OBJECTIVE

Only one of the many unanswered questions is treated in this report: How do different evaporimeters with unrestricted water supplies react, on an hourly basis, to the same meteorological conditions? The analysis of the data was hampered by the fact that the meteorological parameters are highly intercorrelated in the humid tropics so that it is generally not possible to derive formulas applicable to regions with lower intercorrelations.

3. DESCRIPTION OF TECHNIQUES AND EQUIPMENT USED

a. General

The study was conducted in three phases. One phase was conducted during the dry season of 1968, and two during the dry season of 1969. The tests were conducted at the Chiva Chiva open site of the Data Base Project[1], i.e., 9°01'N, 79°35'W, 30 meters above mean sea level. The experiments were arranged in such a way that they did not interfere with the routine measurements being taken in connection with the Data Base Project. Initially the experiments consisted of measurements being made with the Standard Evaporation Pan (also called Class A Pan) and the Piche atmometer, at 4-hour intervals. Later the experiments progressed to strip chart recordings and to the incorporation of other evaporimeters. In these latter phases, test apparatus were located in open areas exposed to sunshine as well as in the shade, with a variety of meteorological measurements being made. Figures 1 and 2 depict a typical arrangement of instruments as used in these experiments.

b. Evaporimeters

(1) Standard Pan and Piche Atmometer. Descriptions of the Standard Pan and the Piche atmometer, as well as a discussion of some of their advantages or disadvantages, can be found in Part I of this series. Additional information concerning the instruments that are of interest to this phase of the study are included in the following paragraphs.

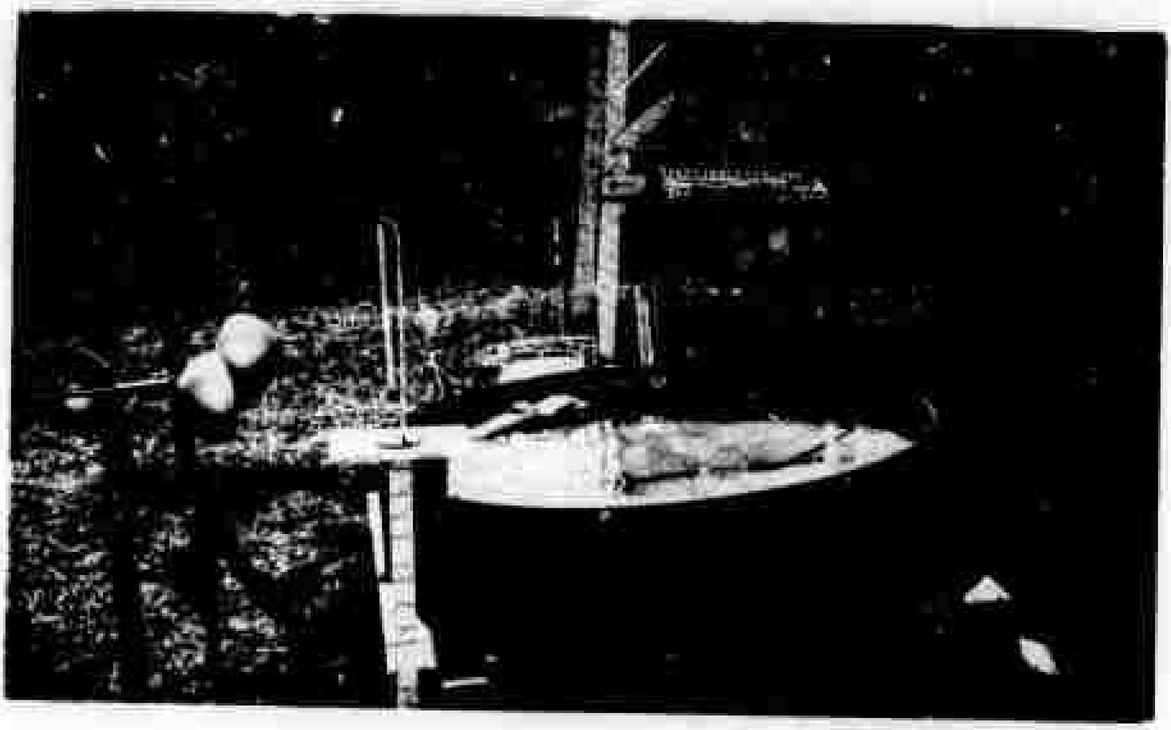


Figure 1. View of a Typical Evaporimetry Test Apparatus Configuration

Although the wind speed never exceeded 8 miles per hour (3.6m/s), the water level in the "still well" rose and fell irregularly when the wind agitated the water surface of the tank. If a climate is moist enough to allow only limited evaporation and if it is windy, the instrument reading errors encountered will sometimes be larger than the actual change in water level.

The water level in the Pan not only depends upon the mass of water but also on its density and hence its temperature. This must be taken into account whenever the water level is measured at different temperatures (paragraph 5a).

Two Piche atmometers are shown in figure 1, one upwind from the Pan, and the other standing close to a recording balance. During the study, the blotting paper under one of the Piches was increased from 32 to 90 millimeters in diameter to increase the resolution capabilities for measurement of the evaporation rate and thus reduce the relative reading error. However, two disadvantages caused the rapid termination of this experimental phase: the mechanical stability of the modified Piche against wind stress was reduced too much, and the instrument had to be refilled too frequently.

One normal Piche stood in a standard thermometer shelter; a second one was hanging free by its upper ring; a third was also hanging, but prevented from swinging by an additional clamp (figure 3).

(2) **Wild Evaporation Weighing Gage.** Several evaporation weighing gages of the type introduced by Wild in 1871 were used. A Wild evaporimeter consists of a brass bowl of 250 square centimeters in area, filled with water and attached to the lever of a balance (figures 1 and 3). The weight of the bowl produces a trace on a strip chart, graduated to indicate a change of water level at constant temperature rather than the weight. Several gages of this type were alternately and/or simultaneously placed in the sun, in the shade, and in the thermometer shelter. During the last series of experiments they were also used to obtain strip chart recordings of the Pan and of the Livingstone atmometer. Details follow in paragraph d, below.

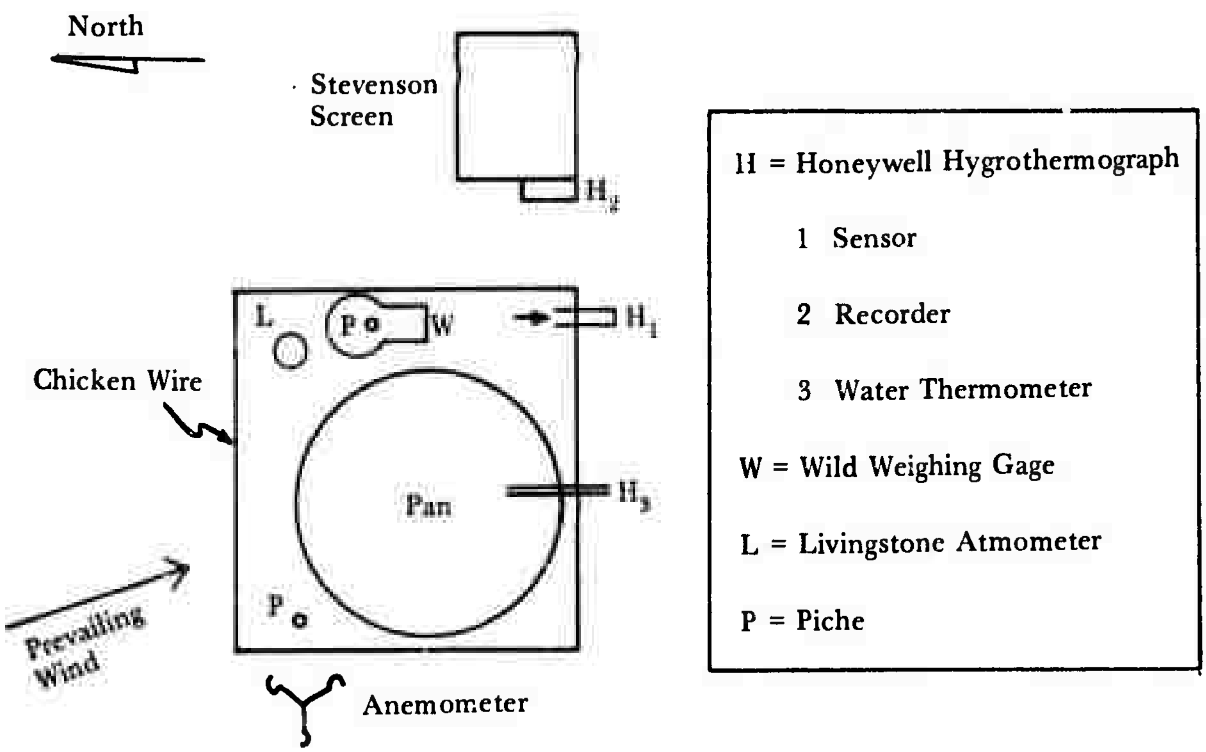


Figure 2. Schematic Layout of a Typical Evaporimetry Test Apparatus Configuration

(3) **Livingstone Atmometer.** A Livingstone atmometer consists of a porous porcelain ball filled with water which penetrates the porcelain at the rate of its evaporation from the ball's surface. The evaporated water is replaced by water from an attached reservoir, the reduction of the water in the reservoir being equal to the amount evaporated. Figures 1 and 3 show this type of atmometer in a typical configuration. In this configuration the water container for replenishment of the evaporated water was a burette. Later the probe also was used in the shade, and the water was sucked up from the bowl of a weighing gage with the water consumption rate being recorded on a strip chart. For details on these observations see paragraph d, below.

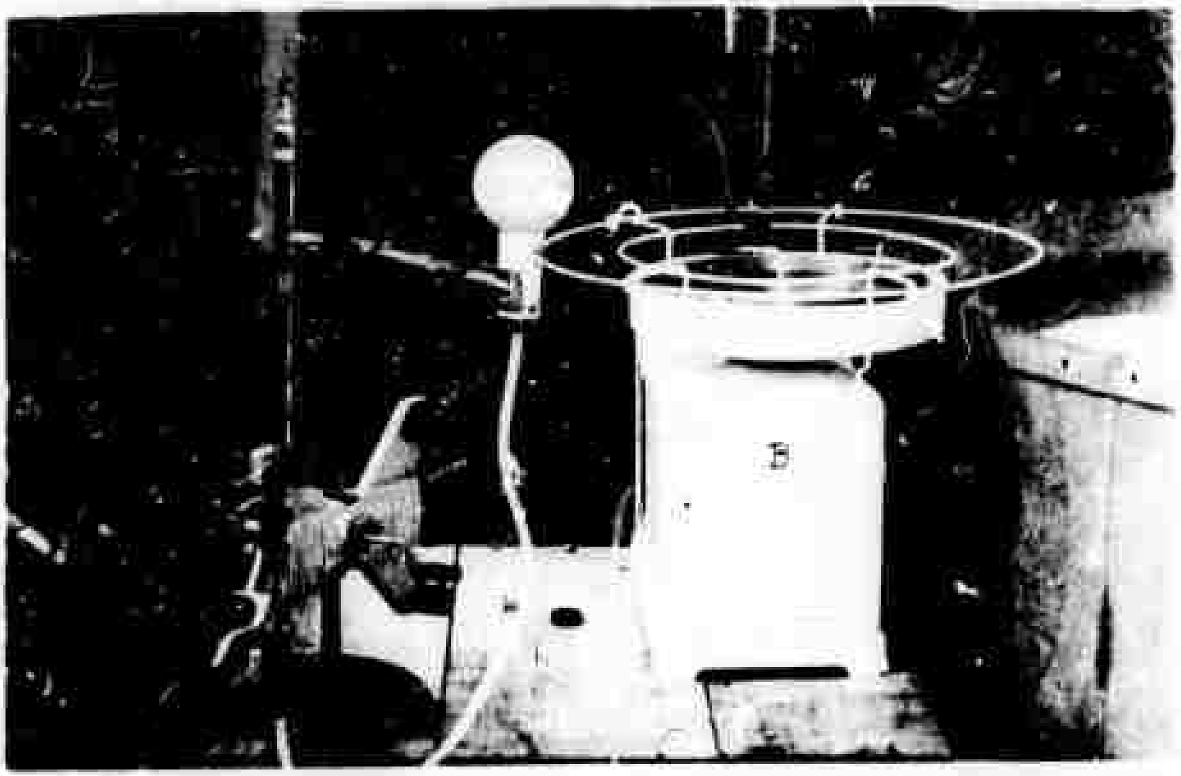


Figure 3. Test Apparatus Set-Up for Livingstone and Piche Atmometer and a Wild Weighing Gage (B)

c. **Other Instruments**

Evaporation is caused by physical processes that can be broken down into components. In these experiments the measured components were wind speed, temperature and humidity of the ambient air, solar radiation, and temperature of the water in the evaporimeters. The following meteorological instruments were used during the course of these experiments:

(1) **Cup Anemometer.** The wind speed was measured with different kinds of cup anemometers; during the experiment in April 1969 it was measured as depicted in figure 1. Later an MRI automatic weather station was installed in the same location as the old anemometer, with its recording cup anemometer at the same height as the previous nonrecording instrument. Test runs before the rearrangement showed exact agreement between the calibrations of the two instruments. The MRI instrument was finally elevated to the height of the thermometer shelter.

(2) **Honeywell Hygrothermograph.** A Honeywell hygrothermograph recorded (a) dry and wet bulb temperatures at the height of the water level of the Pan, and (b) the temperature of the Pan water. The recorder with its three pens was fastened to the thermometer shelter. The temperature sensors were downwind from the Pan and facing into the main wind direction. The soil thermometer was in an inclined position

submerged in the water of the tank (figure 1). Frequent calibrations showed that the effect of solar radiation on the instrument was too small to be measured, while the floating thermometer (figure 1) read several degrees too high during sunshine. This is an important finding because it is quite common to measure the water temperature of an evaporation tank in this fashion.

(3) **Belfort Hygrothermograph.** A Belfort hygrothermograph with 7-day strip charts was running in the thermometer shelter at all times.

(4) **Remote Control Psychrometers.** During the last part of the experiments the entire station was moved approximately 150 feet northward and was close to the Data Base tower. Two of the Cardion-West telethermometers were removed from the tower and placed at the height of the Belfort hygrothermograph in the triangle formed by the tower, the wire cage with the evaporimeters, and the thermometer shelter. Every 5 minutes, these well-aspirated thermometers recorded dry and wet bulb temperatures on punch tape.

(5) **Actinograph.** Near the evaporimeters an actinograph (pyranograph) recorded the global (sun plus sky) radiation. The design features of this instrument were such that the data obtained were relative, but recordings could be calibrated, to a certain extent, by means of the recordings obtained by the US Army Meteorological Team at the Chiva Chiva test site (1400 meters NW of the Chiva Chiva Data Base tower) and on Gun Hill (1750 meters to the SSW).

(6) **Raingauge.** A raingauge was used to record the limited amount of rain that fell during the test period. This permitted the exclusion of rainy periods from the analysis.

d. Modification of Instruments.

In the latter phases of the experiments the Standard Pan and the Livingstone were connected by siphons to recording evaporation weighing gages and provided excellent strip chart recordings. For the Pan siphon, a wooden plate and a plastic collar separated the evaporation bowls from the ambient air. Because of the siphon, the water in the bowl had the same height as the water in the Pan and reflected all of its height changes. The siphon did not touch any moving parts of the weighing gage, and the recorded changes of the water level in the bowl were produced by the changes in the Pan. The accuracy could have been increased through application of two corrections: one for different temperatures of the two water bodies involved and another to correct for the fact that the small bowl was an extension of the entire water mass but was *not* exposed to the ambient air. It was expected that the accuracy of the weighing mechanisms would not warrant the application of such corrections, however, during data analysis it was found that the accuracy of the measurements could have been improved had the temperature of the water in the bowl been recorded.

The Livingstone atmometer was connected to the weighing gage in nearly the same way as the Standard Pan, but with a different siphon arrangement. The rubber hose that assured equal water levels of Pan and gage was replaced with a brass tube leading from the water-filled bowl of the gage vertically up into the porcelain ball. Water evaporating from the latter was replaced with water from the bowl by simple suction. The two corrections described in the previous paragraph do not apply here, because the recorder connected to the Livingstone reacted to the *water mass* in the instrument, whereas the recorder connected with the Pan was activated by changes in the *height* of the water. Regrettably, strip chart recordings of the Piche could not be obtained because the sensitivity of the balance was insufficient to detect the small weight changes of the Piche.

4. OBSERVATIONS

The following paragraphs describe certain observations with pertinent conclusions. They are not a breakdown of all experiments because different experiments were partly overlapping; some were modified for improvement purposes; some were interrupted by rain or animals interfering with the water level in the Pan (although it was surrounded by a wire fence) and resumed later; and some were inconclusive.

a. Different Exposures of Piche Evaporimeters.

Several series of measurements were made to investigate the influence of exposure on the data obtained using the Piche instruments.

(1) Swinging and Fixed Piche. One Piche was hanging in the NW corner of the cage (figure 1), and a clamp prevented it from swinging. Another Piche was freely hanging directly over the bowl of the weighing gage. The global radiation impinging on both instruments can be assumed to have been equal. After several days the clamp was removed from the former and attached to the latter. No effect of the clamp change could be found; in both configurations the Piche over the bowl indicated 77 percent of the evaporation indicated by the Piche in the NW corner. From this observation it was concluded that (a) whether the Piche is swinging makes no difference as long as the wind is not strong enough to force water through the blotting paper by the centrifugal force of swinging or bouncing against the stand; (b) the small difference in height and the small shielding effect of the Pan produced as much as a 23-percent difference in the measurements. Location of exposure of the Piche was found to be of the highest importance for the magnitude of the measured values.

(2) Different Sizes of Blotting Paper. In the series of measurements in which Piches with different sizes of blotting paper were used, the effect of the difference in size cannot be properly assessed because the instruments were never in the same place. An estimate can be obtained from a comparison between two series of measurements; one following the other, under slightly different weather conditions. In both series one normal Piche was hanging over the bowl and served as a standard. In one of the series, the Piche in the NW corner of the measuring plot had an oversized blotting paper of 90mm diameter. In the other series, the paper was of standard size (32mm in diameter).

The evaporation increase was approximately proportional to the increase in area of the blotting paper. Large blotting papers can cause increased water comsumption through dripping, or decreased comsumption through drying of the edge. The former would be an effect of wind; the latter an effect of extremely dry ambient air. It was concluded that the enlargement of the blotting paper above its standard size is impractical.

(3) **Piche in a Stevenson Screen (standard thermometer shelter).** During another experiment one Piche was hanging in the NW corner, another was located in the temperature shelter (Stevenson screen). The values recorded by the latter instrument were 79 percent of the former. It is tempting to conclude that the instrument in the shelter acted in almost the same way as the instrument over the bowl. This, however, was not the case. While the quoted percentages of both instruments were practically equal on the basis of 24-hour periods, they were different for different parts of the day. The instrument over the bowl always recorded 77 percent of that in the NW corner; the sheltered Piche recorded 73 percent of the latter during daytime hours and 98 percent during the night.

The evaporation in the shelter was 91 percent of that of the weighing gage in the open during the day and 120 percent at night.

From these observations it was concluded that the ratio between in-shelter and out-of-shelter evaporation changes during the course of a day. It must be assumed that definite seasonal changes may have effects comparable to the diurnal effects reported here. Although Heigel[2] did not find this effect (perhaps he measured only during the warmer half of the year), the possibility of seasonal and regional effects on the ratio—Piche-in-a-shelter to Piche-in-the-open—should not be overlooked in the analysis of climatological data of evaporation.

b. Evaporation Weighing Gages and Livingstone Atmometers.

(1) **Open Exposure versus Screen.** The evaporation weighing gages reflect qualitatively the same conditions as reported for the Piche in the preceding paragraphs, but quantitatively they are different, as is shown in the following tabulation:

Table I. Ratio of Evaporation in Thermometer Shelter to Evaporation in Northeast Corner of Plot

Comparison	Daytime	Nighttime	24 hours
Between Piches	0.91	1.20	0.99
Between Evaporation Weighing Gages	0.48	4.00	0.55

(2) **Open Exposure versus Shaded Exposure.**

(a) **Weighing Gages.** Another series of comparisons helps to explain the contents of table I. Two evaporation weighing gages were used to record data in an open area for several weeks. One was completely exposed to the weather, whereas the other stood on the ground close to a small stilted shelter with a wide overhanging roof 190cm above the ground. The shelter produced only a modification of the wind flow over the evaporation bowl, but the roof drastically reduced the radiation. Direct sunshine was shielded by the overhanging roof from 0930 to 1410 hours local time (approximately 0900 to 1340 hours true solar time). A substantial amount of sky radiation, including the entire flux from the zenith, was intercepted by the roof. Comparison of the measurements made by the free and by the periodically shielded weighing gages gives some insight into the influence of radiation on the evaporation measurements with a Wild instrument.* The strip charts indicated that at 0930, as soon as the shadow of the roof reached the evaporation bowl, the evaporation dropped to 59 percent of that in the sun, and it stayed at this percentage until the shadow left the bowl in the early afternoon. During the time of reduced evaporation, the water temperature of the shaded instrument was 7°F lower than that in the sun.

Some time after the shadow cast by the sun had left the bowl, the water temperatures of both Wilds became equal. Yet the instrument which previously had been in the shadow evaporated more than the other; sometimes more than twice as much. The reason for this could not be fully determined. The ruggedness of the curves obtained suggests that the wind speed and/or the turbulence were greater near the stilted shelter than in the wire cage. The shelter may have produced a kind of venturi effect beneath it, and the chicken wire may have reduced the wind. Lack of suitable anemometers, however, precluded this determination. The difference in the evaporation rates of both instruments dropped to zero with the nocturnal decrease of wind speed, but because the relative humidity of the air also rose enough at the same time to prevent any evaporation, the last statement is not conclusive. (This is one of the cases mentioned previously in which high intercorrelation among meteorological parameters prevents proper explanation of the observations recorded.)

The observations demonstrated that the Wild gage is highly sensitive to radiation and reacts strongly and quickly to radiation changes.

(b) Livingstone Atmometers. Since only one Livingstone atmometer was available, simultaneous recordings of such instruments in different exposures could not be obtained. The one instrument was recording side-by-side with the Wild gage within the cage for some weeks, and for other weeks side-by-side with the Wild gage under the roof. The shadow reduced the evaporation rate of the atmometer, but this reduction cannot be expressed by a numerical value because the weather during the first exposure period was not the same as during the second, and no simple formula was found to relate the indication of the Livingstone to that of the evaporation weighing gage. Such a formula may exist for daily totals, but hourly evaporation rates are under consideration here.

5. DIURNAL VARIATIONS.

The series of measurements obtained in the experiments reported herein were made during the dry season. In order to demonstrate those results which are typical for the season, only the days with considerable radiation were summarized for the comparison of diurnal changes. The following paragraphs compare the results obtained simultaneously by different evaporimeters and discuss the average meteorological conditions for the same days.

* The comparisons between the Piches in and out of the shelter are based on a limited number of readings per day. The comparison of the Wild instruments is based on continuous strip chart recordings which allow a finer analysis.

a. **Diurnal Variation of Evaporation.**

It has been shown above that the amount of evaporated water can change greatly from one instrument to another with only a small change in location (paragraph 4a). Therefore, this section presents all results in relative units: hourly rates of evaporation in percentages of the daily total.

The readings of all instruments that measure the mass of evaporated water have been used without correction. The readings of instruments that measure the height of the evaporated water column need a correction for water temperature, because the column expands and contracts with temperature changes. The errors introduced by temperature changes do not cancel out in the mean of many diurnal variations because temperature and evaporation are closely correlated. Numerical evaluation of the pertinent formulas shows that temperature effects on the Piche were too small to be considered. However, the correction is considerable for the Pan, because the ratio of its evaporating surface to the cross section of the water container is 1 whereas it is 8.4 for the Piche. Table II lists some of the corrections that had to be applied to the Pan readings. Two other corrections described earlier in the report (paragraph 3d) were not applied for the reasons given. The true solar time differed during the period of the measurements by approximately 30 minutes, e.g., 0900 hours local time corresponds to 0830 solar time.

Table II. Examples of Pan Reading Corrections Caused by Changes in Water Temperature

Time Intervals Local Time (hours)	0400 to 0500	0900 to 1000	1300 to 1400	1700 to 1800	2000 to 2100
Raw Evaporation Rate*	0.10	0.26	0.96	1.04	0.30
Corrected Evaporation Rate**	0.07	0.50	1.09	0.85	0.19

* Scale divisions on the recorder. The unit is irrelevant.

** Assuming a water depth of 10 inches. The correction is proportional to the water depth and to the temperature change during the time interval of rate computation (1 hour in this example).

The relative amount of the maximum reflects the peakedness (also called kurtosis or fourth moment, when numerically expressed using all measurements). The peakedness increases in the order: Standard Pan – Wild in shelter – Livingstone – Wild in the open – Piche. Physically it corresponds to the instrument's speed of reaction to changes in ambient conditions; the Pan being the slowest, the Piche the quickest.

Table III compares the percentages of daytime and nighttime evaporations and supplements the statements of the previous paragraphs.

Table III. **Percentage of Total Evaporation during Day and Night**

	Local Time (hours)	
Instrument	Daytime (0700-1900)	Nighttime (1900-0700)
Standard Pan	87.9	12.1
Wild, in shelter	91.0	9.0
Livingstone	93.5	6.5
Piche	94.6	5.4
Wild, in the open	97.0	3.0

After reaching a maximum, the evaporation rate decreases sharply and drops to zero, or close to zero, for all instruments. During this low evaporation period, the Standard Pan maintains the highest evaporation rate. The heat capacity of the large water mass of the Pan is such that enough energy is available to maintain the vaporization process through the entire night. On the other hand, the same reasoning applies to the sluggishness of Pan evaporation before noon. (Because of some uncertainty in the data reduction, which will be discussed later in paragraph 6, the evaporation curve for the Pan may be less correct between 0800 and 1100 hours than the corresponding curves of the other instruments.)

In addition to the results discussed thus far, figure 4 shows the evaporation curve of the Wild gage that was shaded during part of the day. In this case the percentages do not refer to the total measured with this instrument, but to the total measured with the unshaded Wild, as discussed in paragraph 4b.

b. **Diurnal Variation of Meteorological Parameters.**

Figure 5 illustrates the diurnal variation of several meteorological parameters. The curves refer to the same radiation days as those of figure 4 with the exception that in the latter the Piche data have been taken 16 months earlier, i.e., in January 1968. These are the only hourly Piche data available for Chiva Chiva, and only those days were selected for averaging on which meteorological conditions were similiar to those presented in figure 5. Air temperature and saturation deficit are based on readings taken by the automatic data acquisition system at 5-minute intervals. The other data are based on hourly evaluations of strip charts.

Ambient temperatures were taken at 41 and 141 centimeters above ground; the former being graphed in figure 5 and labelled "Air Temperature 41cm." The rapid temperature increase between 0800 and 0900 hours, and the occurrence of the plateau-like maximum are typical for the humid tropics. A temperature peak which would be expected from corresponding curves obtained in dry, hot climates is cut off by the cloudiness which always develops.

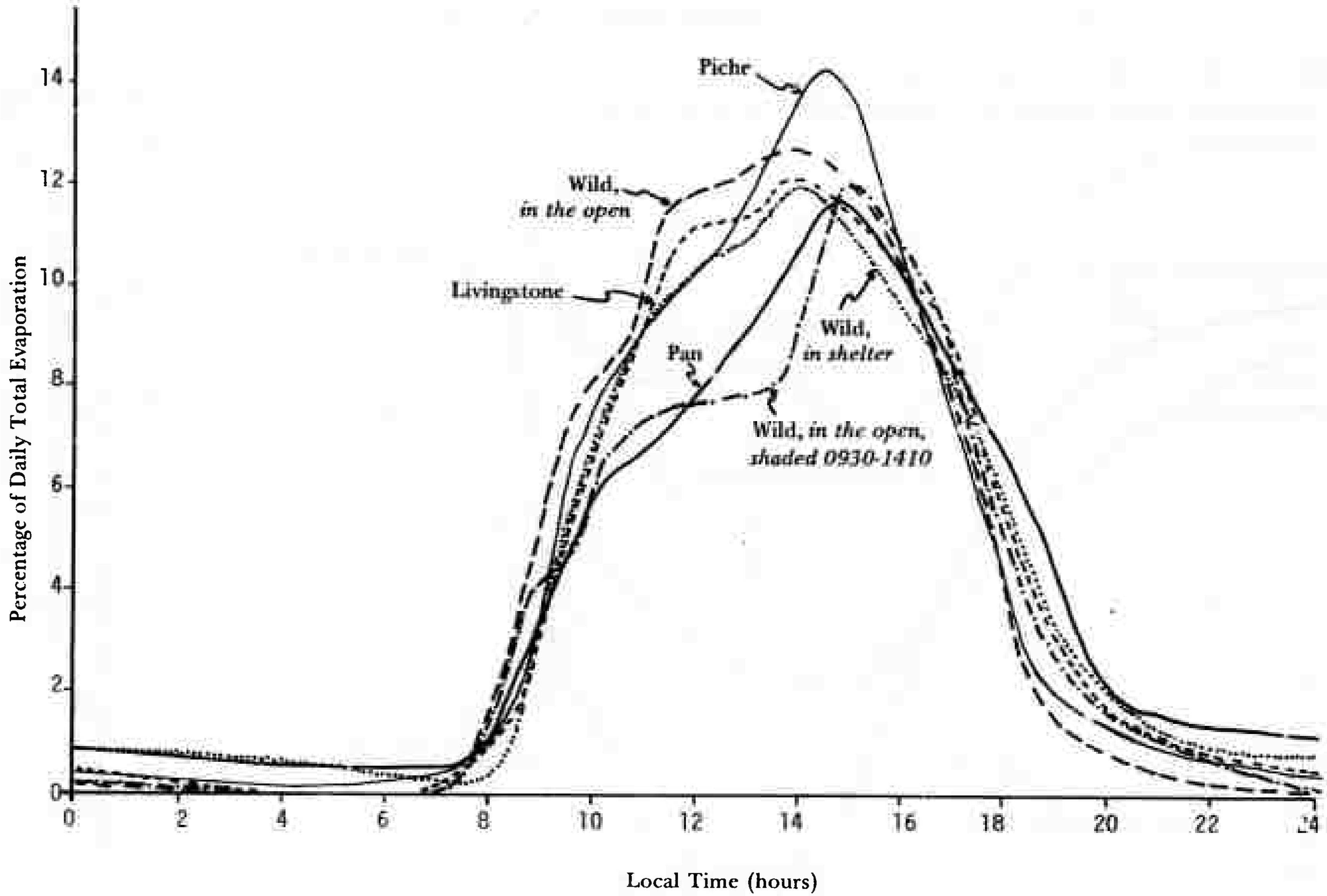


Figure 4. Diurnal Variation of Evaporation Measured with Different Instruments

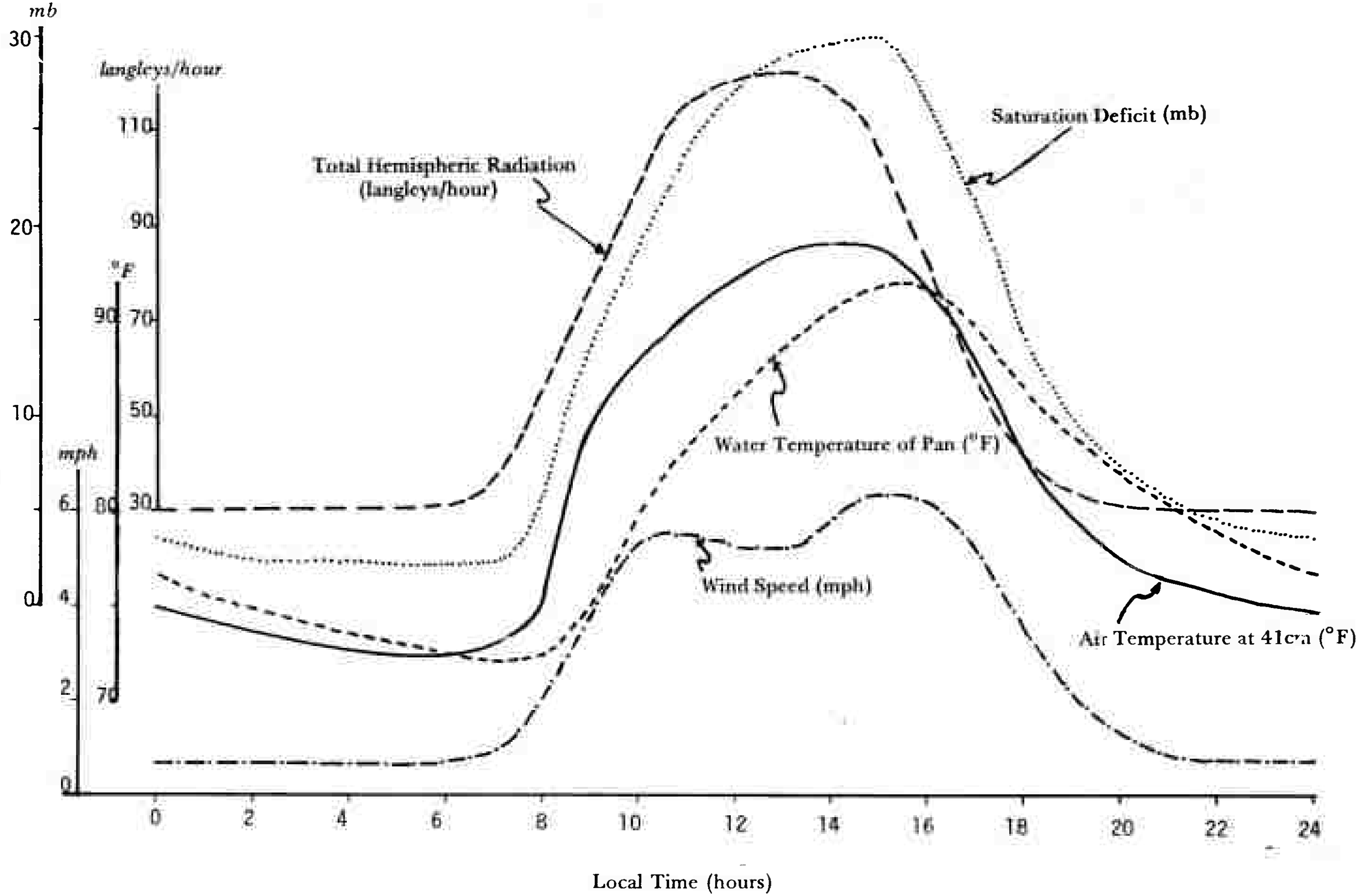


Figure 5. Diurnal Variation of Some Meteorological Parameters

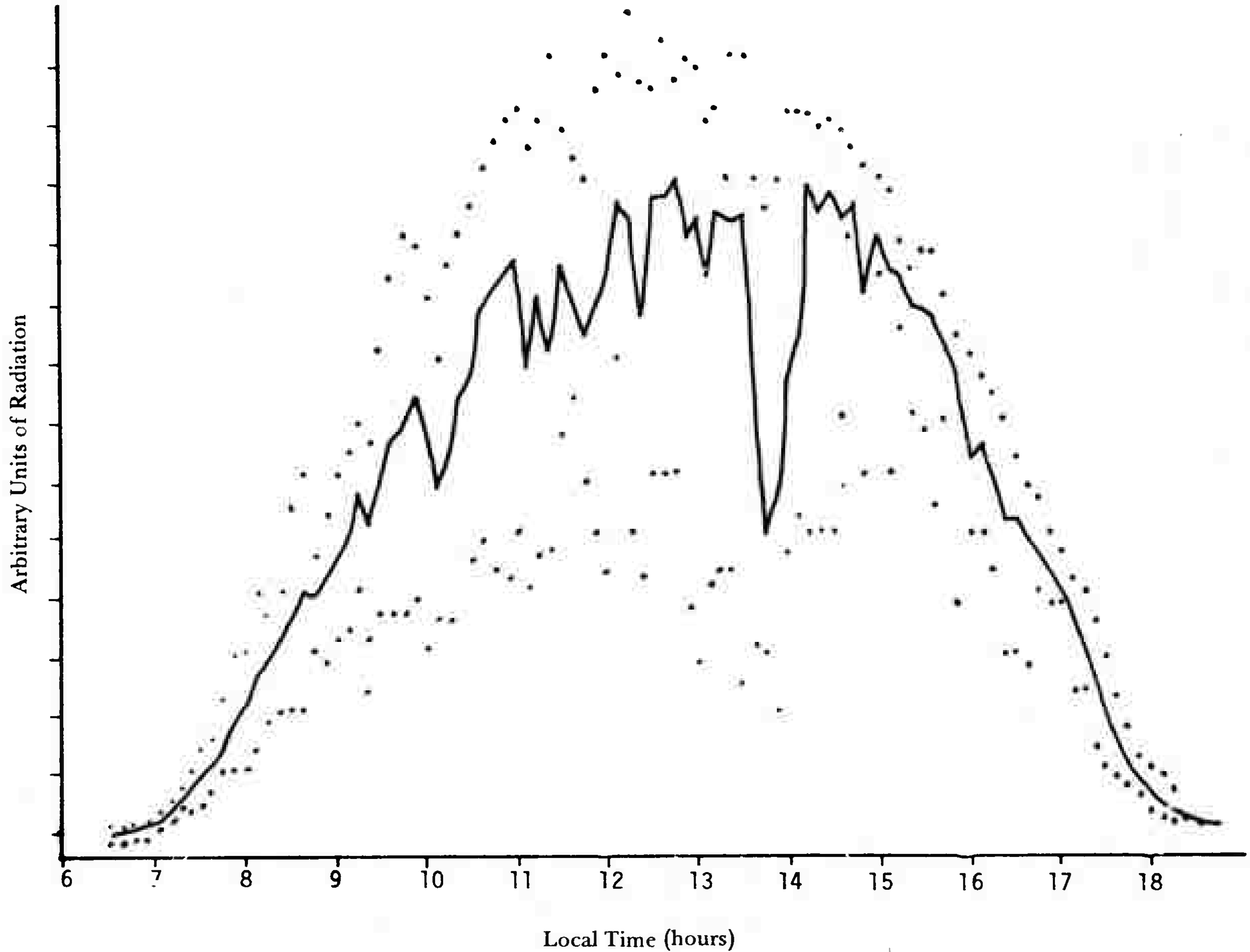
The curve of the mean global radiation shown in figure 5 is based on hourly increments, and since the instrument was on Gun Hill at a distance of 1750 meters, it is appropriate to present a summary of the actinograph recordings although that instrument gives relative, rather than absolute values. Figure 6 shows the actinograph recording read every 7.5 minutes and averaged over the 8 radiation days on which most of the curves of figures 4 and 5 are based. In addition, figure 6 also shows the highest and lowest values read within each 7.5-minute interval. The curve looks quite different from what most meteorologists expect to be typical for the days with greatest radiation in the dry season. Only in the late afternoon is the curve rather smooth and the range between extremes rather small. This is the same time of the day when the evaporation curves of figure 4 required a minimum of smoothing.

The curve of the saturation deficit (figure 5) is generally parallel to the curve of the ambient temperature, with two exceptions. In morning hours the temperature rises faster than the saturation deficit because the increasing heat vaporizes the nocturnal dew and the soil moisture brought to the surface during the night, thus raising the absolute humidity of the air. Contrasting with this, the soil adds practically no more moisture to the air at noon or later, but the turbulence dilutes the low level moisture into higher levels. Through this mechanism the saturation deficit still increases when the ambient temperature has begun to drop. Figure 7 shows the mean vapor pressure at the 41-cm level during the 8 radiation days. The time coincidence of the radiation drop at 1345 hours (figure 6) and the rise of absolute humidity (figure 7) is remarkable. It may be due to the arrival of the sea breeze front. Since this front is poorly developed in the Canal Zone, this conjecture could not be confirmed.

The comparison of the Cardion-West thermometers with the Honeywell hygrothermograph revealed that the latter gives readings of the wet bulb thermometer that are too high during periods of sunshine. This is because its water reservoir heats up and feeds the wet bulb with water which is 10°F and sometimes 20°F warmer than the wet bulb temperature. The resulting error of the wet thermometer is in the order of magnitude of 1.5°F which corresponds to approximately 5 percent relative humidity. The error is greater than for values obtained using other wet bulb thermometers because (1) the water is warmed through the glass container similar to plants in a greenhouse, and (2) the water consumption of the large sensor is considerable so that there is little time for the water to cool to at least the dry-bulb temperature on its way to the sensor.

The wind is a consequence of heat distribution and, hence, reflects the uneven radiation conditions by displaying a secondary maximum late in the morning and its main maximum 1 hour after the maximum of radiation. As observations in previous years show, the double wind maximum develops gradually during February and is typical for March. At that time, the global circulation (trade winds) becomes weaker and is increasingly replaced with local developments.

The temperature of the water in the Standard Pan (figure 5) shows a considerable lag with respect to the temperature of the ambient air, and from 1600 to 0600 hours it is warmer than the latter. The mean daily water temperature was found to be only 0.8°F



Legend: Curve Represents Mean Values
Dots Represent Extreme Values

Figure 6. Mean and Extreme Global Radiation during Eight Radiation Days

lower than the mean air temperature at 41 centimeters above the ground. However, assuming that the water temperature at the place where it evaporates is at the wet bulb temperature, the corresponding difference of mean daily temperature would be 8.2° F. This would be the case with the Piche (Mukammal[3]). As the temperature of the evaporating water has significant influence on the amount of evaporation, *the difference between the water temperatures is one of the main contributors to the discrepancy between measurements made with different types of evaporimeters.* Although not measured, it can be assumed that the water temperatures of the Livingstone and Wild instruments lie between those of the Pan and the Piche, because their involved water masses are greater than those of the Piche and smaller than those of the Pan.

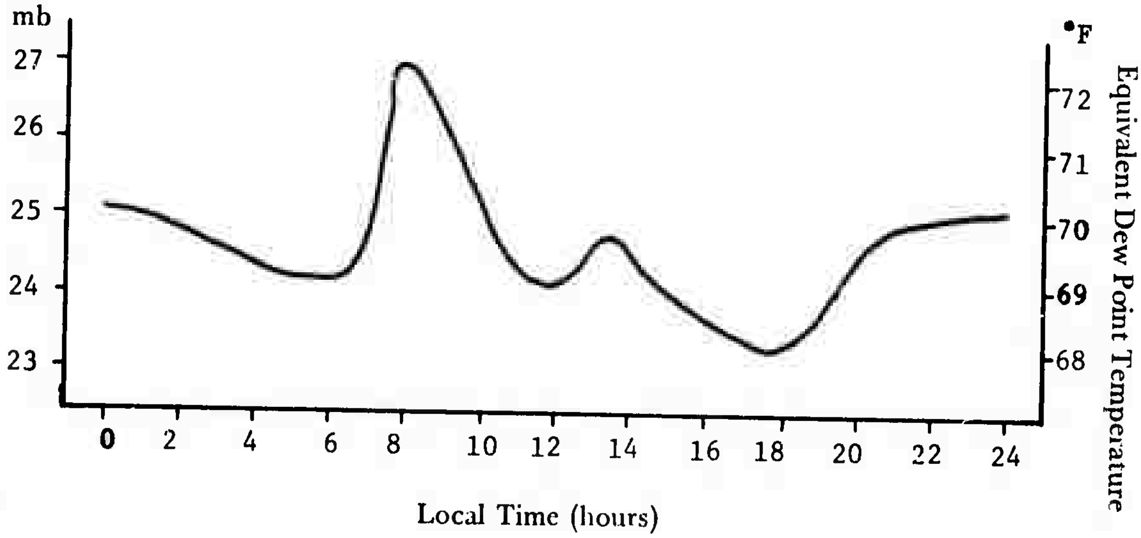


Figure 7. Diurnal Variation of Vapor Pressure at 41 Centimeters above Ground

6. INCIDENTAL OBSERVATIONS

Some phenomena that seem to be worth reporting were noted as by-products of the routine observations. These are discussed in the following paragraphs.

a. Water Temperature of Wild Weighing Gage

The change in the evaporation rate of the Wild gage when a shadow is cast on it, as described earlier in this report, is due to a drop in water temperature as a result of the screening of substantial amounts of radiation.

When the ambient temperature was rising sharply and a shadow moved to shade the bowl, the water temperature rose slowly. However, when the ambient temperature was falling, and the covering shadow moved away, the water temperature in the evaporation bowl changed rapidly in an unexpected manner: The water temperature rose rapidly from 83°F to 87°F, but remained there for only a few minutes before the increased rate of evaporation and the resultant evaporative cooling lowered the temperature rapidly to 85°F. The water temperature then fell slowly to the upper 70s at sunset. After the transition from the rapid to the slow temperature drop, the water temperatures of both this gage and the unshaded gage were equal. (Note: As mentioned in Section 4b(2), the evaporation rates were not equal at that time.)

The effect of radiation on the water temperature depends on the height of water in the bowl, but this effect was not large enough to be detected in the observations under investigation. The correlation coefficients between height of water and rate of evaporation were negative but were too small to meet the 10-percent level of significance.

b. Water Temperature of the Pan-Recorder System.

The temperature changes of the evaporating water clearly affect the evaporation rate, but the temperature changes of the nonevaporating water in the bowl of the Pan recorder also had an influence on the recorded amount. When the temperature of the bowl water is higher than that of the Pan water, thermal expansion causes some water flow from the bowl to the Pan which appears on the strip chart as increased evaporation. This effect was deemed insignificant when the experiments were carried out, but the data show a correlation between amount of water in the bowl and evaporation trace in the morning when the small water mass in the bowl warms up rapidly while the large water mass in the pan does so slowly. It is estimated that the temperatures of the two water masses differ by as much as 10°F, but measurements of this difference have not been made. Such measurements are strongly recommended for similar future investigations. It is further recommended that measurements be made of the temperature of the tank water at different depths.

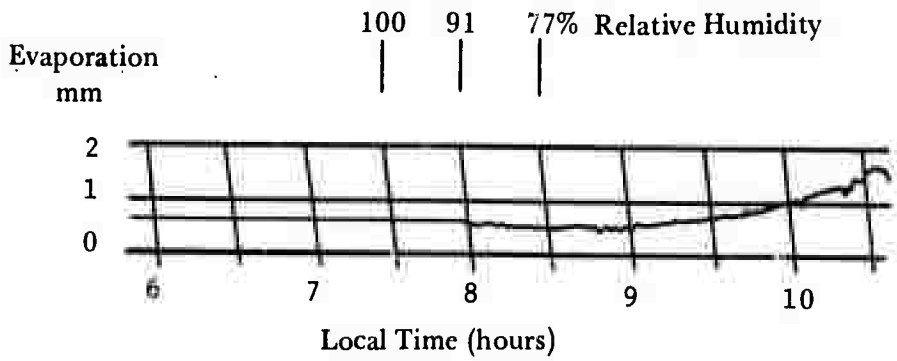
c. Dew Formation on Water Surfaces.

Dew formed on the water surfaces of the evaporimeters on some days. For instance, on 11 April 1968 the grass was very wet with dew at sunrise. After sunrise the temperatures of the grass and the overlying air rose rapidly and the dew evaporated in a very short time. Table IV shows some measurements taken on the day when this process was taking place and it can be inferred from it that, because vapor condensed on the water surface, the water temperature at 0730 hours was lower than the dew point of the air. In fact, the Pan (table IV) as well as the open Wild gage (figure 8) indicated the presence of the condensation, which in this case was minute. Such a condensation on water may be of some importance when warm and very moist air is advected over cold water (as may happen in spring months over the Great Lakes during an invasion of warm air from the South).

Table IV. Evaluation Condensation Measurements*

Hours	0730	0800	0830	0930
		Local Time (hours)		
Air temperature (°F)**	72.8	76.1	80.9	83.4
Relative humidity (%)**	100	91	77	68
Dew point (°F)**	72.8	73.2	73.1	71.8
Water temperature of Pan (°F)	72.5	73.3	75.0	76.3
Water level in Pan, raw (in)	2.562	2.561	2.565	2.560
Water level in Pan, Corrected for water temperature (in)	2.562	2.560	2.563	2.556
Evaporation (+), Condensation (-) (in)		+0.002	-0.003	+0.007

* Taken on 11 April 1968
** At 50 cm above ground.



NOTE: Relative humidity of the ambient air is noted above the curve; the small dip of the curve at 0755 hours indicates the beginning of the condensation on the water.

Figure 8. Evaporation Weighing Gage Recording at the Time of Dew Formation on the Water on 11 April 1968

7. SUMMARY OF RESULTS

The following paragraphs provide a summary of the results discussed throughout the text.

a. The commonly used floating thermometer of the Standard Pan indicates, during sunshine, a temperature several degrees too high [paragraph 3c(2)].

b. Wild evaporation weighing gages are very sensitive to radiation [paragraph 4b(2) and 5a]—possibly too sensitive to be of any value. They can, however, be used to produce strip chart recordings of the Standard Pan or the Livingstone atmometer. When they are used as recorders for the Pan, the water temperature in the bowl of the weighing gage should be permanently recorded, because this temperature is necessary for a refinement of the temperature corrections (paragraph 3d and 5c).

c. A freely swinging Piche evaporates the same amount of water as a fixed one as long at it does not bounce against the stand or swing violently. Enlargement of the blotting paper is not recommended because the relative decrease of reading errors is offset by the increase of other errors [paragraphs 4a(1) and (2)].

d. Details of the exposure of the Piche can have substantial effects [paragraph 4a(1)]. The diurnal variation of a Piche within a Stevenson screen is different from that of a Piche in the open. The same holds for the weighing gage; however, the degree of difference is not the same [paragraph 4b(1)].

e. Equal meteorological conditions produce *different* reactions of different evaporimeters. This holds for the amount as well as for the timing (paragraph 5a).

f. Honeywell hygrothern ographs indicate wet bulb temperatures which are too high when the water reservoir is exposed to sunlight. The error can be as much as 5 percent relative humidity in the humid tropics (paragraph 5b) and is much larger under sunny dry conditions.

g. Variations in water temperature produced by dissimiliar design and/or operational characteristics are a major reason for the fact that different evaporimeters react differently to the same weather conditions (paragraph 5b and appendix II).

h. Dew may form on water, i.e., negative evaporation of a water surface may occur (paragraph 6c).

8. CONCLUSIONS

When it became apparent that evaporation was a complicated process, the concept *potential evaporation* was introduced, which restricted the evaporation cases under consideration to those in which water was always available to keep the process going.

Each of the evaporimeters discussed in this report has an ample water supply with no (or only very small) changes of the interface between the water and the ambient air. Hence, they measure potential evaporation. Yet, their output is not equal nor even proportional (figure 4).

From this disparity it was concluded that (a) evaporation is not merely a meteorological quantity, (b) potential evaporation is not a quantity that can be measured with a relatively simple instrument and compared universally.

A brief insight into the theory which explains the difficulties of the problem through the flux of heat into the evaporating water, is given in this report (appendix I). It is relegated to an appendix because it does not contain any ideas that have not been published before.

Because there are a large number of workers in the field of evaporation who are still attempting to solve the problems through the use of the discussed instruments, the foregoing experiments were conducted. The fact that the experiments were conducted in the humid tropics is of importance only because they supplement similar experiments made at higher latitudes.

The huge amount of evaporation data accumulated during the last hundred years by different kinds of evaporimeters is probably of some use. They can be used when and where natural evaporation processes, that are correlated to the processes within an evaporimeter, are found. This is, for instance, the case with the evaporation of lakes which resembles the evaporation from a Pan (Roberts and Stall[4], with extensive bibliography). In the course of the many investigations of this kind, the authors have developed formulas that can be used to compute the lake evaporation from meteorological data (plus some universal parameters) rather than from evaporimeters; evaporimeters were downgraded to meteorological summarizers whose measurements must be multiplied by a seasonal and geographically variable factor to yield an estimate of natural lake evaporation.

Other evaporimeters, including those discussed in this paper, may also be useful indicators of natural evaporation processes. *Per se*, they do not yield any more insight than into their own evaporation. It is useless to ask which of the evaporimeters is best as long as no relationship to natural processes has been established. Without such a relationship data from any evaporimeter are inconsequential.

SECTION B. APPENDICES

APPENDIX I. THEORETICAL ASPECTS OF EVAPORATION

1. GENERAL

A complete general theory of evaporation does not yet exist, and it is doubtful that it ever will (Berenyi[5]). Simplification of the problem was attempted by dividing the evaporation processes into two groups; one in which the evaporating surface is always kept wet, and the other where the water supply is sometimes, or always, restricted. The first group is called "potential evaporation." Some authors hope that methods will be found that link the actual to the potential evaporation either through statistics or through better understanding of the water supply mechanisms.

2. ACTUAL EVAPORATION.

Not much is known about actual evaporation because all attempts to measure it affect the process itself. Attempts were made under Project TREND* to measure the actual evaporation from soil as well as from branches of plants (the latter process called transpiration). Theoretical treatment of the process would involve an assessment of the balance between the suction force of the air (evaporative power) and the pressure forces such as capillarity for soil and osmosis for plants. Apparently, the scientific community is still far from a solution to this problem, but there is no doubt that the understanding of actual evaporation processes would be beneficial in many fields of science, engineering, and agriculture.

3. POTENTIAL EVAPORATION.

A discussion of four different approaches to the understanding of potential evaporation follows:

a. Correlations.

The most common approach to potential evaporation is a correlation of measured or estimated values with wind speed and saturation deficit over the evaporating surface. Usually the method is refined by replacing the saturation deficit with the difference between the actual vapor pressure of the air and the saturation vapor pressure at the water surface temperature. All these attempts end in an empirical formula of the general type $E = a(e_w - e_a)(1 + bv^c)$ in which E is the rate of evaporation; e_w and e_a are the saturation vapor pressure at water temperature and the actual vapor pressure of the air; v is the wind speed at some specified height over the water surface; and a, b, c are constants. The latter three vary from author to author depending on how the E values were obtained. Such a formula can only be a rough approximation and cannot be generalized. For example, it does not explain the steaming of hot, wet ground or of warm water.

*An environmental study, similar in many respects to the Environmental Data Base Project[1] carried out in Thailand under the sponsorship of Natick Laboratories.

b. **Water Balance.**

A more sophisticated approach to the understanding of potential evaporation is the consideration of the water balance. It is reasoned that the total of the water movements involved in precipitation, evaporation, run-off (at the soil surface), and seepage (into the soil) is zero. This reasoning is applied particularly in the study of entire watersheds; but the uncertainties of measurement are considerable and accumulative with respect to evaporation because, in the water balance equation, the evaporation is the small difference between relatively large amounts of precipitation on one hand, and run-off and seepage on the other.

c. **Energy Balance.**

In this approach an attempt is made to compute the thermal energy going into and coming out of a volume which consists of water in its lower part and air in its upper[6]. One of the heat flux components is the heat of vaporization which is directly proportional to the mass of evaporated water. Hence, when all other heat fluxes are known, the evaporation can be computed. Again, as in the case of the water balance, the individual fluxes are not well enough known to allow computation of the evaporation with a better than fair degree of accuracy. The heat balance considerations can be applied to areas of any size and are not restricted to watersheds or entire lakes. A special difficulty in this type of computation lies in the proper assessment of the amount of heat carried away by the wind. This part of the problem is extremely difficult in its physical background as well as its mathematical treatment. Solutions are obtained only under the assumption that the atmosphere is adiabatically stratified immediately above the evaporating surface. This, however, is practically never the case. In the Chiva Chiva experiments described herein, the temperature lapse rate between 41 and 141 centimeters over the ground at noon time was 100 times as great as the adiabatic and became negative at night. The assumption of adiabatic stratification of the air leads to a formula in which the potential evaporation is proportional to the decrease of water vapor with height. In Chiva Chiva, however, there was generally a slight increase of vapor pressure with height; yet evaporation occurred.

The actual problem of the heat balance method is more deeply rooted: No theory adequately describes the movement of air very close to the ground under any possible vertical temperature differences. While in the free atmosphere air rises through buoyancy when the lapse rate exceeds the adiabatic, lapse rates of more that 2000 times the adiabatic have been measured immediately over the ground, and no unusual vertical movements were noted. Baum[7] calculated, with the use of very simplifying assumptions, that a lapse rate of 6°C/cm would be the maximum possible in the 1-centimeter-thick layer of air directly over the ground. This is 60,000 times the adiabatic lapse rate by which the present state-of-the-art allows computation of the potential evaporation from exchange and flux theory.

Figure 5 shows the great differences between the water temperatures of the Standard Pan and the air at 41 centimeters over ground. When it is assumed that the height of the thermometer was 5 centimeters higher than the water surface of the Pan, we arrive at lapse rates oscillating between $-2.5°C/5cm$ and $-0.5°C/cm$ at 1900 and $+5.5°C/5cm$ and $+1.1°C/cm$ at 0900, whereas the lapse rate used in the heat flux theory is the adiabatic which is $-0.0001°C/cm$. (The height between water surface and thermometer for the air temperature was variable because the water level changed through evaporation; also, the air temperature was not measured over the Pan, but approximately 2 meters away.)

d. Hofmann's Approach.

Hofmann[8] tried to explain the formation of dew, rime, and frost. But, as evaporation is the reverse of dew formation, his reasoning can be and has been (Roth[9]) applied to evaporation processes. His work resulted in a formula of the form:

$$E = a(B + S) + bv^{0.75} (100 - RH)$$

In this formula, E is the rate of evaporation, B is the flux of sensible heat through matter other than air to the evaporating surface, S is the net radiation (equals radiation balance) of that same surface, v is the wind speed, and RH is the relative humidity of the air. The letters a and b do not denote constants as they do in paragraph a, above, but mathematical functions of the temperature; b is, in addition, very strongly dependent on the form and size of the evaporating surface.

Discussion of the formula reveals the basic difficulties in the evaluation of evaporation measurements. B represents the heat fluxes through the walls of the container as well as through the water itself to its surface. These fluxes depend on the radiation received by the container and on the temperature difference between ambient air and water, a difference that changes rapidly in the course of the day. S depends on the amount of incoming radiation, the wavelength of this radiation (because the absorptivity of the evaporimeter is dependent on it), and the (constantly changing) temperature of the evaporating surface. We may neglect the relatively simple dependence of b on the temperature, but the form factor which is a part of b varies considerably and is not known in detail.

Considering all the factors condensed into Hofmann's formula, one must conclude that the real potential evaporation from any evaporating device, i.e., from any evaporimeter, differs—the meteorological conditions being equal—with the form of the device and with its heat conduction characteristics. The evaporation from any surface is not a meteorological parameter alone, but is always strongly influenced by the evaporating body including the mass below the evaporating surface. The consequence is that measurements are only comparable if they have been made with the same kind of instrument in the same kind of exposure. The usefulness of such a comparison depends on the special conditions under which the comparison is made.

This theory holds only for cases in which water is readily available, i.e., in the case of potential evaporation in general, and of the instruments discussed in this report in particular. If water has to rise to the evaporating surface through capillary or osmotic forces, the conditions become more complicated not only because the availability of water must be considered but also because the variables B and S in Hofmann's formula become the sum of two B's and two S's; one each referring to the water, the others to the dry matter.

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