VENEZUELAN INTERNATIONAL METEOROLOGICAL AND HYDROLOGICAL EXPERIMENT (VIMHEX)

HYDROLOGY REPORT

VOLUME IV

SOIL TEMPERATURES AND HEAT CONTENT

by

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November 1971

CER70-71MAS-DBS-EVR-50

The VIMHEX hydrological data and analyses are being presented in a series of VIMHEX hydrology reports. This fourth volume contains data collected at the Anaco soil temperature station, the analyses of those data, and estimates of the amount of heat stored in the soil throughout a 24-hour period.

Volume I, Precipitation Data and Analysis, contains the precipitation data collected by VIMHEX during the summer of 1969.

Volume II, Streamflow, Groundwater and Ground Response Data, is a presentation of most of the other hydrological information collected by VIMHEX.

Volume III, Geometric and Hydraulic Properties of the Rivers, is a study of the relations between discharge, velocity, roughness, and cross-sectional geometry of the principal rivers in the study area.

Further analyses of the hydrological data will be published in other volumes of the VIMHEX hydrology reports.

November 1971

FOREWORD

The project leaders for VIMHEX are Dr. H. Riehl, Atmospheric Science Department, Colorado State University and D. B. Simons, Civil Engineering Department, Colorado State University. VIMHEX is sponsored by the Department of Defense through its THEMIS program. In addition to the financial support provided by the Department of Defense, professional members of the various branches of the Armed Services are contributing significantly to the solution of logistics, management and scientific problems. Mr. James Hughes, Office of Naval Research, who is the Contracting Officer for VIMHEX, has been especially helpful.

ABSTRACT

VIMHEX is an intensive program of tropical meteorological and hydrological observations taken in northeast Venezuela during the summer of 1969 to support a study of tropical atmospheric physics and the resulting effect of rainfall.

The objectives of the program are to express the meso-scale weather structure in terms of the synoptic-scale envelope and to formulate the ground response to the rainfall produced by tropical weather disturbances over relatively flat tropical topography.

During the period from 1800 hours on September 29 to 2400 hours on September 30, 1969, soil temperature and soil moisture content profiles were measured in the top 24 inches of the ground at the Anaco raingage site. From these data, the hourly heat content of the upper 24 inches of soil has been computed for the period.

From 1800 hours on September 29 to 1000 hours on September 30, the heat loss from the upper 24 inches of soil was approximately 2 langleys per hour. In the next four hours, the soil gained energy at a rate of approximately 9 langleys per hour. Thereafter until midnight on September 30, content remained nearly constant. The maximum change in heat content was 22 langleys per hour between 1200 and 1300 hours on September 30.

The night-time rate of decrease in soil thermal energy determined in this study agree closely with night-time long wave back radiation values reported by Renné (1970) for the same area.

ACKNOWLEDGMENTS

The Venezuelan International Meteorological and Hydrological Experiment (VIMHEX) was conducted by Colorado State University with participation by the National Center for Atmospheric Research, the U. S. National Guard Bureau, The Venezuelan Air Force Meteorological Service, the Venezuelan Minister of Public Works, the Venezuelan National Institute of Sanitation, the Central University of Venezuela, the Eastern University at Jusepín, the Bonn Institute, the Imperial College, Mobile Oil Company of Venezuela and IBIDEM Company of Venezuela.

The measurements of soil temperatures and moisture contents presented in this report were made by J. H. Duke, Jr. and the data were processed by V. C. Duke.

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CHAPTER I

INTRODUCTION

The Venezuelan International Meteorological and Hydrological Experiment (VIMHEX) was an intensive program of tropical meteorological and hydrological observations taken in northeast Venezuela during the summer of 1969 to support a study of tropical atmospheric physics and the resulting effects of rainfall. The general study area is outlined on Figure I-1.

The objectives of the program are: (1) to express the meso-scale (10-50 mile) weather structure in terms of the synoptic-scale (1,000 mile) envelope; (2) to formulate prediction methods from this weather model for runoff from streams, ground trafficability and groundwater variations; (3) to contribute to the understanding of the role of meso-scale weather to large-scale weather; and (4) to observe the extent and severity of equatorial zone thunderstorms relative to that encountered in other areas.

In the short-period energy balance for the atmosphere, the soil mass acts as a diurnal thermal source and sink. Thermal energy obtained from or through the atmosphere is stored in the soil during one part of the day and released during other periods. This termal energy in the soil can affect the ground area water balance as well as the water balance in the atmosphere.

The thermal energy stored in and released from the soil during a diurnal cycle can be measured directly. In the interest of the VIMHEX studies, the thermal energy in the soil at the Anaco raingage site was measured.

During the period from 1800 hours on September 29 to 2400 hours on September 30, 1969, hourly measurements of the soil temperature profile and moisture content profile in the top 24 inches of soil were made at the Anaco raingage site. These data were reported in the VIMHEX Hydrology Report, Volume II (1971) and are reproduced in this report in Chapter II along with some additional information on the properties of the soil.

With measurements of soil temperature and properties of the soil, the variations in soil heat content can be computed. Expressions relating heat content, soil properties and soil temperature are developed in Chapter III.

The variations of soil heat content at the Anaco raingage site for the 30-hour period between 1800 hours on September 29 and 2400 hours on September 30, 1969, are determined in Chapter IV. The results and conclusions are presented in Chapter V.

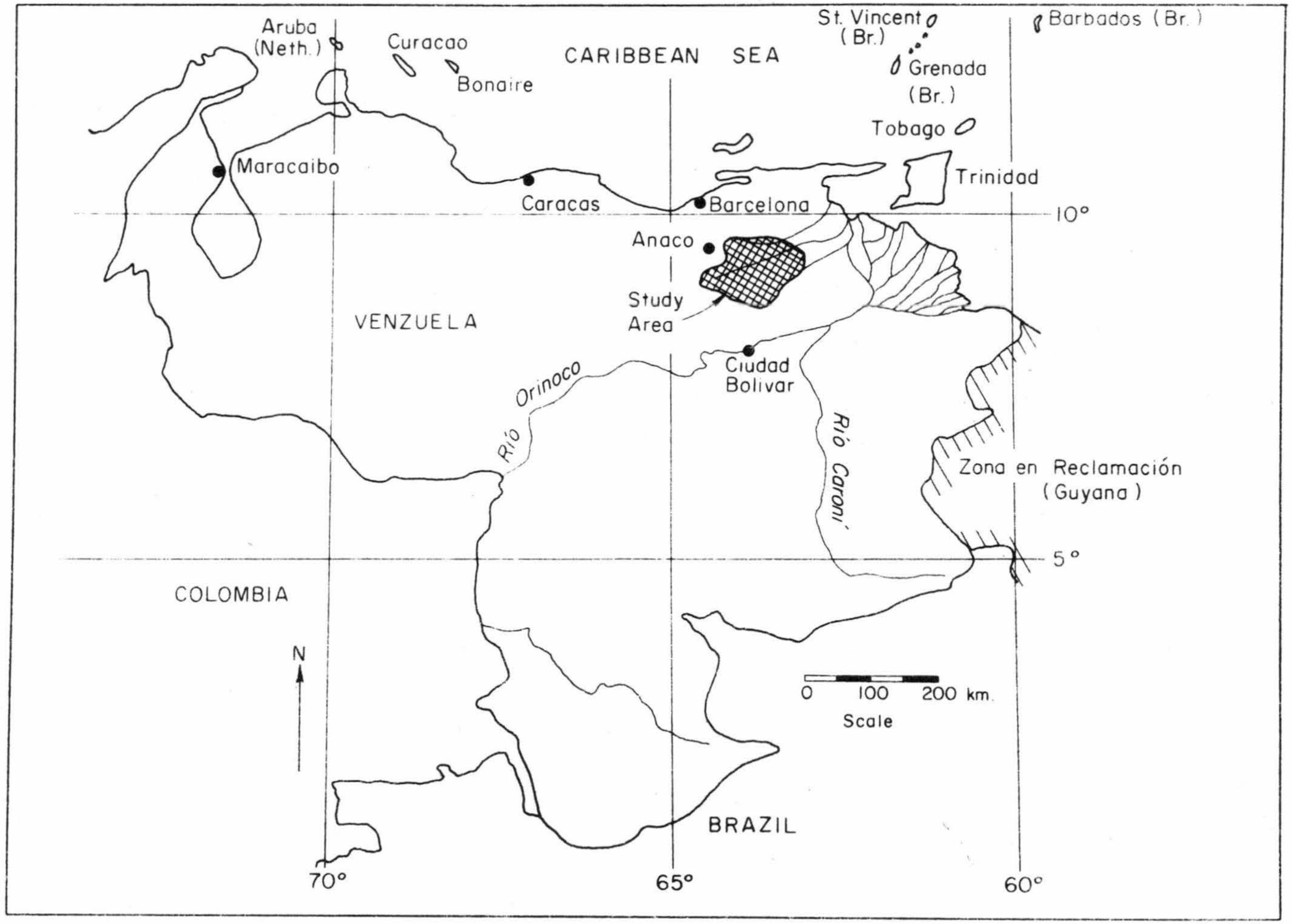

FIGURE I-1 LOCATION OF STUDY AREA

CHAPTER II

DATA

Measurements of soil temperature, soil moisture, and other properties of the soil were made in the upper 24 inches of the ground at the Anaco raingage site during the month of September, 1969. The soil temperature and moisture data and the particle size analysis have been previously reported in Volume II of the VIMHEX Hydrology Reports. Other data are reported here for the first time.

For the determination of the variation in soil heat content, the study period is from 1800 hours on September 29 to 2400 hours on September 30, 1969. During this period hourly readings of soil temperature and soil moisture content were taken.

SOIL TEMPERATURE

The soil temperature data for the study period are presented in Table II-1. This information was obtained from Volume II of the VIMHEX Hydrology Reports (1971). A description of the instrumentation can be found in Volume II.

SOIL PROPERTIES

Samples of soil taken at the Anaco raingage site were analyzed for particle size distribution and for other index properties. In Table II-2, the particle size analysis indicates that the vertical distribution of soil material is homogeneous as to size. The composite sieve size distribution is shown on Figure II-1. Ninety-four percent of the total weight of the composite soil sample is sand; the remainder is finer-sized silts and clays. The median diameter of the composite soil is 0.3 mm.

Other properties of the soil are given in Table II-3. In determining the volume of solids in a sample, it was assumed that the unit weight of the solid particles was 2.65 gm/cc. This value is the normally reported unit weight for sand. The void ratios at different levels below the ground surface indicate that the sand is normally packed (neither dense or loose) except for a layer between 15 and 21 inches below the surface. There, the sand is loosely packed.

SOIL MOISTURE

Soil moisture observations were made at the Anaco raingage site during the period between July 8 and October 2, 1969. The complete description of the soil moisture observation program and tabulated data are given in the VIMHEX Hydrology Report, Volume II, (1971). For that period pertaining to the soil temperature data collection program, the soil moisture observations (tensiometer readings) are reproduced in Table II-4. A soil that is completely saturated would have a tensiometer reading of zero atmospheres tension and if the soil were completely dry, the reading would be 1.0 atmospheres tension.

In the late evening of September 28, 8 mm of precipitation occurred at the Anaco site and between 1800 and 1900 hours of September 30 another 0.5 mm of rain fell. The 0.5 mm of rainfall was not reflected in the tensiometer readings at the 6-inch depth level so it has been assumed that the average of the tensiometer readings at the 5 different depths are sufficiently representative of the soil moisture content during the period from 1800 hours on September 29 to 0000 hours on October 1. The averages are given at the bottom of Table IV.

In order to obtain the relationship between tensiometer reading and degree of saturation, the tensiometer must be calibrated in place in the soil. At the same time that soil samples were taken, the tensiometer readings were also obtained. The tensiometer calibration data are given in Table II-5 and the calibration curve is shown on Figure II-2.

The average dry weight of the soil and the degree-of-saturation profile through the top 36 inches of soil is shown on Figure II-3. The straight line on Figure II-3 has been selected as representing the degree-of-saturation profile with sufficient accuracy for heat content calculations.

TABLE II-1

SOIL TEMPERATURE DATA

Anaco Raingage Sta. No. WG 1
(Temperature in deg F)

Time	Air Temp.	Distance below ground surface, in. -2	-1	0	+1	+2	+3	+4	+6	+12	+24
September 29											
1805-1900	79.2	78.0	78.0	80.2	--	84.0	84.4	84.5	84.4	85.0	84.9
1910-1945	79.0	77.3	77.2	79.8	82.4	83.1	83.6	84.0	84.0	84.9	84.6
2000-2040	78.6	77.1	78.3	79.7	82.4	83.4	83.2	83.8	83.7	84.8	84.6
2130-2210	77.4	77.1	75.9	78.6	81.8	82.4	82.7	83.5	83.4	84.8	84.7
2225-2300	77.6	75.1	75.4	78.0	81.4	82.8	82.4	83.4	83.6	85.0	84.7
2330-2350	76.4	74.4	73.6	77.1	80.4	82.2	81.9	82.8	82.8	84.5	84.8
September 30											
0005-0050	76.8	74.1	74.0	76.8	80.5	82.0	82.1	82.6	82.8	84.2	84.2
0105-0135	77.0	73.3	72.7	76.0	79.3	81.1	80.9	82.3	82.2	84.4	84.3
0200-0230	76.8	72.0	--	75.2	79.0	--	80.9	81.8	82.0	84.4	--
0300-0352	76.0	72.3	72.2	75.2	79.0	--	80.5	81.6	81.0	84.0	84.4
0400-0440	75.6	73.6	73.7	76.0	79.2	80.2	80.6	82.2	81.6	83.7	84.3
0505-0550	75.0	73.8	74.2	76.4	79.1	80.3	--	81.3	81.7	83.8	85.0
0600-0645	76.5	73.7	73.2	75.6	78.9	80.3	80.7	80.7	82.6	83.7	84.6
0700-0730	79.6	76.4	76.0	78.1	78.8	80.0	79.6	80.8	81.0	83.0	84.1
0800-0830	82.5	79.6	78.8	80.7	79.7	80.4	81.9	80.6	80.8	82.6	83.6
0900-0925	85.0	83.4	82.2	81.4	79.9	80.0	--	80.5	81.0	82.2	83.2

TABLE II-1 (continued)

SOIL TEMPERATURE DATA

Anaco Raingage Sta. No. WG 1
(Temperature in deg F)

Time	Air Temp.	Distance below ground surface, in. -2	-1	0	+1	+2	+3	+4	+6	+12	+24
September 30 (cont.)											
1000-1025	83.3	84.8	85.0	84.2	80.2	80.4	--	80.8	80.1	81.6	82.2
1100-1120	90.0	89.2	88.4	87.4	81.0	80.7	--	80.8	80.8	81.6	81.6
1200-1215	92.5	95.0	93.8	92.4	82.0	81.4	--	80.8	80.8	81.0	82.4
1300-1325	93.2	96.9	95.8	95.7	84.3	83.4	83.6	83.5	82.9	82.8	84.0
1400-1420	92.4	90.7	90.8	--	88.0	86.4	--	85.5	84.6	84.1	85.0
1500-1520	94.8	95.5	94.4	94.4	87.3	86.0	--	85.1	84.8	83.2	84.1
1600-1626	87.6	90.6	88.6	90.2	86.2	85.5	85.3	84.8	84.8	82.8	83.8
1700-1720	81.2	77.4	76.2	80.0	84.5	85.3	85.2	84.6	84.0	84.2	84.6
1800-1825	79.2	76.8	76.9	80.4	83.7	83.8	--	84.2	84.3	84.5	84.4
1900-1925	80.4	74.4	74.6	78.7	81.8	82.4	81.6	83.9	--	84.5	--
2000-2015	79.4	--	75.5	79.6	82.1	83.6	83.1	83.8	83.5	84.9	84.2
2100-2115	79.2	75.8	75.8	78.9	81.8	82.9	82.6	83.4	83.2	84.9	84.6
2200-2217	78.5	75.2	75.5	78.0	79.9	82.3	82.5	83.8	83.8	85.2	84.5
2300-2315	78.6	75.4	75.8	78.0	80.8	82.0	81.8	82.6	82.5	84.4	83.4
October 1											
0001-0011	77.8	75.6	76.2	77.6	80.7	81.9	82.0	82.8	83.7	85.2	--

TABLE II-2

SOIL PARTICLE SIZE ANALYSIS

ANACO RAINGAGE SITE*

Sample number	Distance below the surface in.	Percent by weight finer than 8 mm	4 mm	2 mm	1 mm	0.5 mm	0.25 mm	0.125 mm	0.0625 mm
1	6	100.0	99.9	99.3	94.6	85.5	37.0	14.1	7.1
2	12	100.0	99.8	99.2	94.0	85.0	35.7	12.2	5.7
3	18	--	100.0	99.2	94.1	85.9	37.8	12.9	5.9
4	24	--	100.0	99.6	94.2	85.9	35.2	12.1	5.6
5	36	--	100.0	99.6	94.5	86.5	40.1	13.8	6.4
Composite	6 to 36	100.0	99.9	99.4	94.3	85.8	37.2	13.0	6.1

* After VIMHEX Hydrology Report, Volume II (1971)

TABLE II-3

PROPERTIES OF THE SOIL

Sampled Depth	Volume Sampled cc	Weight of Solids gm	Weight of Moisture gm	Moisture Content %	Volume of Solids cc	Volume of Voids cc	Void Ratio	Degree of Saturation %
3" to 9"	40.59	68.65	4.47	6.51	25.91	14.68	.577	30.4
9" to 15"	40.59	69.87	3.70	5.29	26.37	14.22	.539	26.0
15" to 21"	40.59	59.85	3.29	5.50	22.58	18.01	.797	18.3
21" to 27"	40.59	68.21	4.04	5.93	25.74	14.85	.577	27.2
30" to 36"	40.59	64.43	2.67	4.15	24.31	16.28	.669	16.4
Composite								
3" to 27" and 30" to 36"	202.94	331.00	18.17	5.49	124.91	78.03	.625	23.3

TABLE II-4

ANACO TENSIOMETER READINGS

(Units are 0.01 atmospheres tension)

Date	Hour	Depths below ground surface, in. 6	12	18	24	36
Sept. 29	0655	44	52	18	34	22
29	1700	44	54	20	35	22
29	1900	45	54	20	35	21
29	1945	44	54	20	35	22
29	2040	44	54	20	35	21
29	2215	44	54	20	35	21
29	2305	45	54	19	35	22
29	2355	45	54	19	35	21
Sept. 30	0055	45	53	19	35	22
30	0145	44	53	18	34	21
30	0235	44	52	18	34	21
30	0352	44	52	18	34	21
30	0435	44	52	18	34	21
30	0543	44	52	17	34	20
30	0645	44	52	17	34	20
30	0730	44	52	17	34	20
30	0825	44	52	17	34	20
30	0925	44	52	17	34	19
30	1025	44	52	17	34	18
30	1120	44	52	16	34	18
30	1215	44	52	15	34	17
30	1325	44	52	16	34	17
30	1420	44	54	19	34	17
30	1520	44	55	18	35	18
30	1625	44	55	19	35	19
30	1720	44	55	20	35	20
30	1825	44	56	19	36	21
30	1929	44	56	22	36	21
30	2015	44	56	22	36	21
30	2115	44	56	20	36	21
30	2217	44	56	20	36	21
30	2315	44	56	20	36	21

TABLE II-4 (continued)

ANACO TENSIOMETER READINGS

(Units are 0.01 atmospheres tension)

Date	Hour	Depths below ground surface, in.				
		6	12	18	24	36
Oct. 1	0011	44	56	20	36	21
1	0700	44	56	18	34	20
1	1700	44	58	22	38	20
Average for the period 1800 hours on Sept. 29 to 2400 hours on Sept. 30		44	54	19	35	20

TABLE II-5

ANACO TENSIOMETER CALIBRATION

Depth Below Surface in.	Tensiometer Reading atm. tension	Degree of Saturation* %
6	.00	30.4
12	.05	26.0
18	.04	18.3
24	.07	27.2
36	.10	16.4

* Obtained from Table II-3

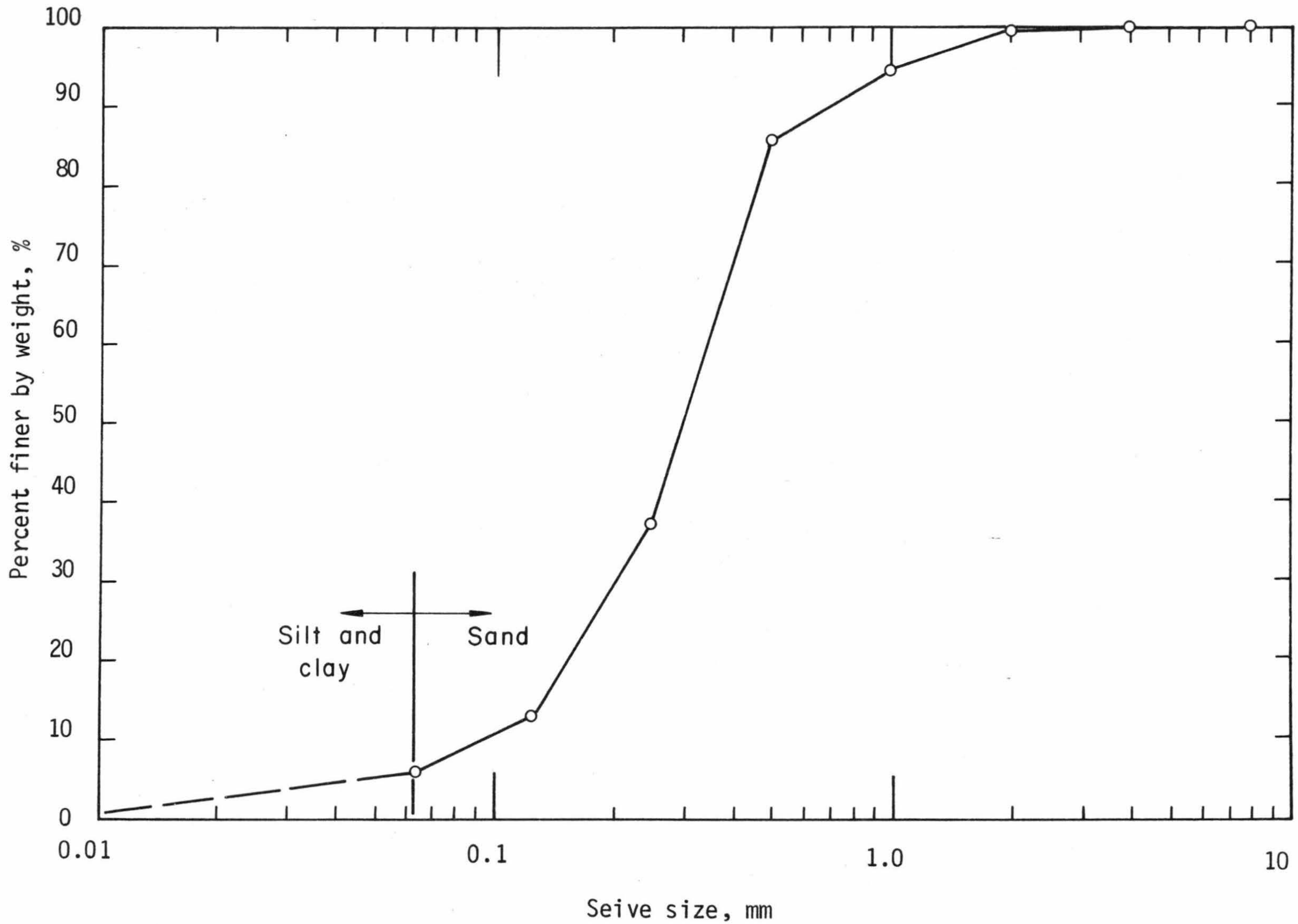

FIGURE II-1 PARTICLE SIZE DISTRIBUTION FOR THE UPPER 24 INCHES OF SOIL AT THE ANACO RAINGAGE SITE

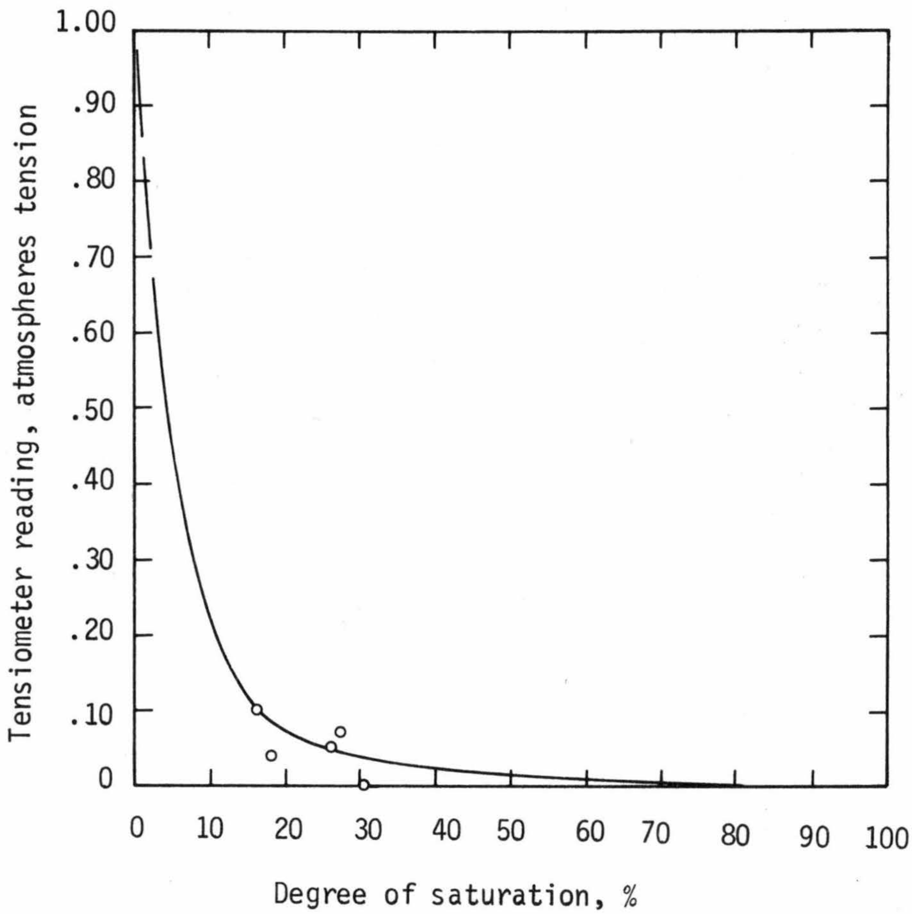

FIGURE II-2 TENSIOMETER CALIBRATION CURVE

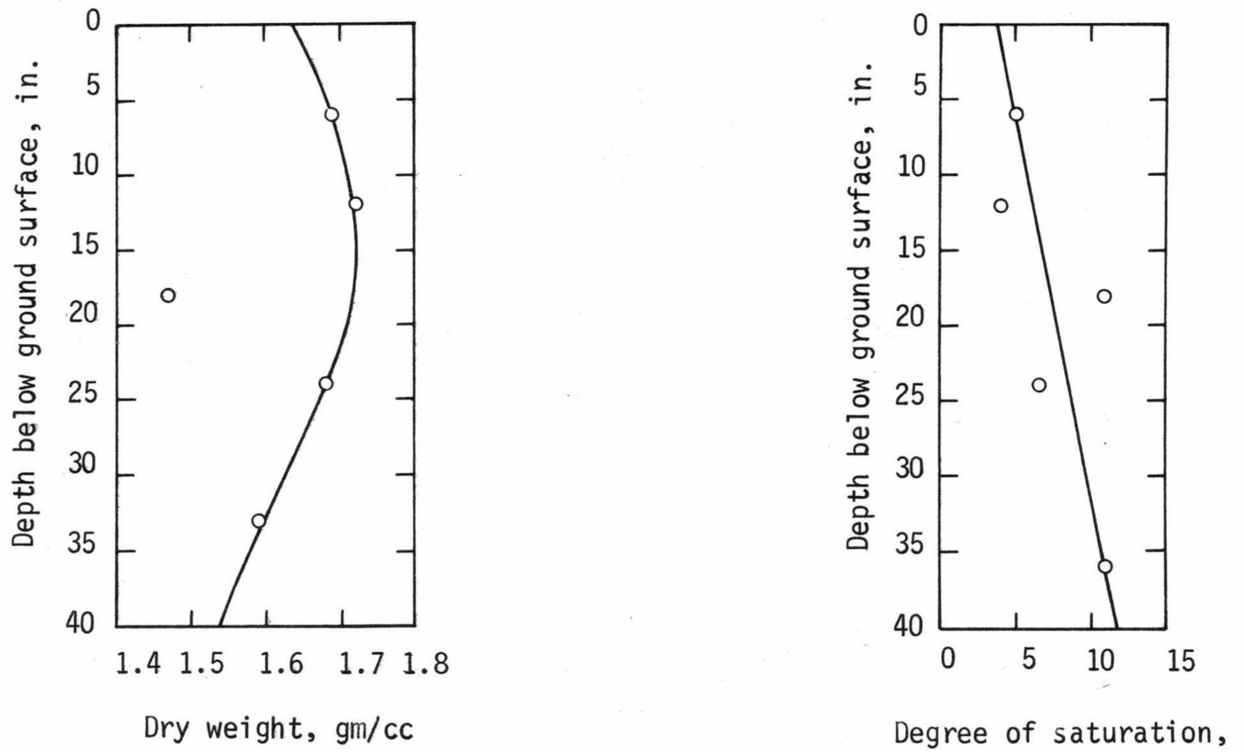

FIGURE II-3 VARIATIONS OF DRY WEIGHT AND DEGREE OF SATURATION WITH DEPTH

CHAPTER III

HEAT CAPACITY OF SANDY SOILS

For the purposes of this study, soil is considered to be a composite mixture of solid sand particles, water, and air. If a given volume of soil is at a constant temperature throughout, the specific heat (heat capacity per unit weight) of the soil mixture, c_o, is given by the expression

$$c_o = c_s + c_w \frac{W_w}{W_s} + c_a \frac{W_a}{W_s}$$

and the amount of heat stored in a unit volume of soil is

$$H = c_o W_s (T-T_o)$$

The terms c_s, c_w, and c_a are the specific heats of the solids, water, and air respectively in cal/gm/°C; W_s, W_w, and W_a are the weights, in gm/cc of solids, water, and air respectively in the unit volume of soil; and T is the temperature of the soil mass in degrees centigrade. The temperature T_o is the temperature to which the heat content, H, is to be referenced. It is convenient to choose T_o nearly equal to T so that the change of c_o with $T-T_o$ can be ignored.

The specific weight of dry air is approximately 0.0011 gm/cc, whereas the specific weight of water is 1.00 gm/cc. The soil solids have a specific weight approximately 2.65 times that of water.

For soils composed almost entirely of sand, the specific heat of the solids can be approximated by the expression for the specific heat of silicon dioxide which is 0.177 cal/gm/°C at 25°C [Hodgman, 1951]. The specific heat of air-free water is 0.998 cal/gm/°C and the specific heat of water-free air is 0.171 cal/gm/°C (constant volume) at the same reference temperature, 25°C.

In the terminology of soil mechanics, the ratio W_w/W_s is called the moisture content, m. A given volume of soil is composed of a volume occupied by the solid particles, V_s, and the remainder called the volume of voids, V_v. The ratio V_v/V_s is the void ratio, e. A portion of the voids contain a volume of water, V_w, and the ratio V_w/V_v is called the degree of saturation, S. The weight of the solids, W_s, is the product of the unit weight of the solid particles, γ_s, and the volume of solids, V_s.

With the definitions given above, the useful relations

$$W_s = \frac{\gamma_s}{1 + e}$$

and

$$m = eS \frac{\gamma_w}{\gamma_s}$$

can be developed. The term γ_s is the unit weight of water.

The capacity of soil to store heat, K, can be written as

$$K = (c_s + mc_w + c_a \frac{W_a}{W_s}) W_s$$

or

$$K = (c_s + c_w eS \frac{\gamma_w}{\gamma_s} + c_a e(1-S) \frac{\gamma_a}{\gamma_s}) (\frac{\gamma_s}{1 + e})$$

in terms of the degree of saturation and the void ratio.

For sands, c_s has been determined and γ_s can be taken as 2.65 gm/cc.

Then

$$K = (.177 + 1.00 \times \frac{.998}{2.65} eS + .171 \times \frac{.0011}{2.65} e(1-S)(\frac{2.65}{1 + e})$$

$$= \frac{.469 + .998\ eS + .000188\ e(1-S)}{1 + e}$$

which can be approximated as

$$K = \frac{.47 + eS + .0002\ e(1-S)}{1 + e}$$

This last expression for the heat capacity of sandy soil can be written as

$$K = \frac{\frac{.47}{e} + S + .0002(1-S)}{\frac{1}{e} + 1}$$

As the weight of solid particles in a unit volume of soil decreases, the void ratio increases. In the limit as the void ratio approaches infinity ($e \to \infty$), there are no solids remaining in the unit volume and

$$K = S + .0002(1-S)$$

The maximum heat capacity factor that a sandy soil can have is when the soil is saturated (S=1) and in the limit ($e \to \infty$)

$$K_{max} = 1.00\ \text{cal/cc/°C}$$

that is, in the limit the soil volume is entirely water. The minimum heat capacity factor for a sandy soil is obtained when the soil is dry (S=0) and in the limit ($e \to \infty$)

$$K_{min} = .0002\ \text{cal/cc/°C}$$

that is, in the limit the soil volume is entirely air. For the natural sand deposits, the void ratios have values in the range between 0.20 (very dense sand) and 0.95 (very loose sand).

It is apparent that the term .0002 e(1-S) is not significant in the expression for the heat capacity factor for sandy soil so that

$$K = \frac{.47 + eS}{1 + e}$$

Comparisons of the properties of loose and dense sands are made in tabular form below.

For a given heat input into a sandy soil, the rate of temperature rise in the soil is inversely proportional to the heat capacity factor, K. That is, loose moist sand will exhibit smaller increases in temperature than loose dry sand for the same heat input.

	Loose Sand	Dense Sand
Void ratio, e	0.95	0.20
Specific weight, γ_s	2.65 gm/cc	2.65 gm/cc
Dry unit weight, W_s	1.36 gm/cc	2.21 gm/cc
Fully saturated, S = 1.00		
Moisture content, m	35.8%	7.6%
Heat capacity factor, K	.73 cal/cc/°C	.56 cal/cc/°C
Dry, S = 0.00		
Moisture content, m	0%	0%
Heat capacity factor, K	.24 cal/cc/°C	.39 cal/cc/°C

CHAPTER IV

ANALYSES

In this chapter, the amount of heat moving into or from the upper 24 inches of the ground at the Anaco raingage site on an hourly basis (approximately) for the period from 1800 hours on September 29 to 2400 hours on September 30, 1969 is determined. Application is made of the equations and measured field data presented in the previous chapters to determine the amount of heat stored and released from the upper ground surface during the 30-hour period.

REFERENCE TEMPERATURE

The time variation of the soil temperature at the ground surface and 24 inches below the surface are shown on Figure IV-1. At the 24-inch level, the soil temperature remained almost constant at a value between 84°F and 85°F except for the period between 0800 hours and 1300 hours on September 30. During this time period the temperature at the 24-inch depth dropped to a value of 81.6°F. The indication is that surface temperature variations are still reflected slightly at the 24-inch depth in the soil, but that major changes in temperature are limited to the upper few inches of the soil mass.

The arithmetic mean of the 31 recorded temperatures at the 24-inch level during the 30-hour study period is 84.1°F which is equivalent to 29.0°C. Therefore 29.0°C will be used as the reference for heat storage computations.

DETERMINATION OF THE HEAT CAPACITY FACTOR

The heat capacity factor, K, was defined in Chapter III as

$$K = \frac{H}{(T-T_o)} = c_o W_s$$

where c_o is the specific heat of the soil. The expression for c_o is

$$c_o = 0.177 + m$$

for sandy soil. The term m is the moisture content of the soil. From the properties of the soil determined in Chapter II, the heat capacity factors for the different layers of soil were computed. The results are given in Table IV-1. The heat capacity factors were computed in the following manner.

For the upper-most layer of soil (0 in. to 1 in.), the dry weight, W_s = 1.64 gm/cc, was obtained from the smoothed curve on Figure II-3 and the degree of saturation, S = 4%, was obtained from the same Figure. The moisture content was computed from the equation

$$m = S\left(\frac{1}{W_s} - \frac{1}{2.65}\right)$$

which is obtained by combining the relationships between moisture content and degree of saturation with the expression relating void ratio and dry unit weight. In this example

$$m = .04\left(\frac{1}{1.64} - \frac{1}{2.65}\right) \times 100$$

$$= .93\%$$

The specific heat of a unit volume of soil is

$$c_o = (0.177 + m)$$

$$= (0.177 + .0093)$$

$$= 0.186 \text{ cal/gm/°C}$$

The heat capacity factor is

$$
\begin{aligned}
K &= c_o W_s \\
&= 0.186 \times 1.64 \\
&= .306 \text{ cal/cc/}^\circ\text{C}
\end{aligned}
$$

HEAT CONTENT OF THE SOIL

The heat content of a layer of soil one sq cm in area and y cm deep is

$$H = K(T-T_o)y$$

In this study, the reference temperature, T_o, has been selected as 84.1°F (29.0°C). The values of K for the different layers of soil are given in Table IV-1. The value of T to be used is the arithmetic average of the measured soil temperatures at the top and bottom of the layer.

The heat content of the various layers of soil at the Anaco raingage site are given in Table IV-2. For illustrative purposes, the computations for the heat content of the layer of soil 3 to 4 inches below the ground surface on September 30 at 1400 hours is given below:

1. In Table II-1, for September 30 at 1400-1420 hours, the soil temperature at the 4-inch depth is given as 85.5°F; the soil temperature at the 3-inch depth is missing. This missing temperature is estimated to be the average of the temperature at a depth 2 inches below the surface, 86.4°F, and of the temperature 4 inches below the surface, 85.5°F. The average temperature for the layer is

$$T = \frac{86.0 + 85.5}{2} = 85.75^\circ\text{F}$$

2. In Table IV-1, the heat capacity factor, K, for the soil layer 3 to 4 inches below the ground surface is given as 0.313 cal/cc/°C.

3. The heat content of the soil layer is

$$\begin{aligned} H &= K(T-T_o)y \\ &= 0.313 \times (85.75 - 84.1) \times \frac{5}{9} \times 1 \times 2.54 \\ &= 0.73 \text{ cal/sq cm of area} \\ &= .73 \text{ ly} \end{aligned}$$

4. For the purpose of plotting, it is assumed that heat content, 0.73 ly, for the soil layer 3 to 4 inches below the ground surface is the heat content at the time mid-point between the beginning and end of the soil temperature observations; i.e., at 1410 hours.

The total heat content of the top 24 inches of soil is given in Table IV-2 and is plotted on Figure IV-2. The heat content of the upper 24 inches of soil decreased steadily from 1800 hours on September 29 to a minimum at 1000 hours on September 30. The heat content increased rapidly between 1200 and 1400 hours on September 30, then remained nearly constant for the rest of the day.

The average rate of heat loss in the upper 24 inches of soil was 2.2 ly/hr between 1800 hours on September 29 and 1000 hours on September 30. Between 1000 hours and 1400 hours on September 30, the energy gain in the soil was approximately 9 ly/hr. The maximum increase in heat content was approximately 22 ly/hr between 1200 and 1300 hours on September 30.

TABLE IV-1

HEAT CAPACITY FACTORS

Layer	Dry weight W_s, gm/cc	Degree of Saturation S, %	Moisture Content m, %	Heat capacity factor K, cal/cc/°C
0" to 1"	1.64	4.0	.93	.306
1" to 2"	1.65	4.2	.96	.308
2" to 3"	1.66	4.5	1.01	.310
3" to 4"	1.67	4.7	1.04	.313
4" to 6"	1.68	5.0	1.09	.316
6" to 12"	1.71	5.5	1.14	.322
12" to 24"	1.72	7.5	1.53	.331
24" to 36"	1.62	10.0	2.40	.326

TABLE IV-2

HEAT CONTENT OF THE SOIL

(Reference temperature is 84.1°F)

Hour	Heat Content of Layer, ly							
	0"-1"	1"-2"	2"-3"	3"-4"	4"-6"	6"-12"	12"-24"	0"-24"
September 29								
1830	-1.27	-0.46	0.04	0.15	0.31	1.64	4.76	5.17
1930	-1.30	-0.59	-0.33	-0.13	-0.09	0.95	3.64	2.15
2020	-1.32	-0.52	-0.35	-0.27	-0.31	0.41	3.36	1.00
2150	-1.68	-0.87	-0.68	-0.44	-0.58	0.00	3.64	- 0.61
2240	-1.90	-0.87	-0.66	-0.53	-0.54	0.55	4.20	0.25
2340	-2.31	-1.22	-0.90	-0.77	-1.16	-1.23	3.08	- 4.51
September 30								
0030	-2.35	-1.24	-0.90	-0.77	-1.25	-1.64	0.56	- 7.59
0120	-2.79	-1.70	-1.35	-1.10	-1.65	-2.18	1.40	- 9.37
0215	-3.02	-2.00	-1.60	-1.22	-1.96	-2.45	1.68	-10.60
0325	-3.02	-2.07	-1.75	-1.35	-2.50	-4.36	0.56	-14.50
0420	-2.81	-1.91	-1.62	-1.19	-1.96	-3.95	- 0.56	-14.00
0530	-2.74	-1.91	-1.55	-1.35	-2.32	-3.68	1.68	-11.90
0620	-2.96	-1.96	-1.57	-1.50	-2.19	-2.59	0.28	-12.50
0715	-2.44	-2.04	-1.88	-1.72	-2.85	-5.72	- 3.08	-19.70
0815	-1.68	-1.76	-1.29	-1.26	-3.03	-6.54	- 5.60	-21.20
0910	-1.49	-1.81	-1.75	-1.66	-2.99	-6.82	- 7.85	-24.40
1010	-0.82	-1.65	-1.57	-1.50	-3.26	-8.86	-12.33	-30.00
1110	0.04	-1.41	-1.46	-1.46	-2.94	-7.91	-14.01	-29.20
1205	1.34	-1.04	-1.25	-1.39	-2.94	-8.72	-13.45	-27.40

TABLE IV-2 (continued)

HEAT CONTENT OF THE SOIL

(Reference temperature is 84.1°F)

Hour	Heat Content of Layer, ly							
	0"-1"	1"-2"	2"-3"	3"-4"	4"-6"	6"-12"	12"-24"	0"-24"
September 30 (cont.)								
1310	2.55	-0.11	-0.26	-0.24	-0.80	-3.41	- 3.92	- 6.19
1410	2.29	1.35	0.92	0.73	0.85	0.68	2.52	9.34
1510	2.92	1.11	0.74	0.55	0.76	-0.27	- 2.52	3.29
1615	1.77	0.76	0.57	0.42	0.62	-0.82	- 4.48	- 1.16
1710	-0.80	0.35	0.50	0.35	0.18	0.00	1.68	2.26
1810	-0.89	-0.15	-0.09	0.00	0.13	0.82	1.96	1.78
1910	-1.66	-0.87	-0.92	-0.60	-0.18	0.27	2.24	- 1.72
2005	-1.40	-0.54	-0.33	-0.29	-0.40	0.27	2.52	- 0.17
2105	-1.62	-0.76	-0.59	-0.49	-0.71	-0.14	3.64	- 0.67
2210	-2.22	-1.30	-0.74	-0.42	-0.27	1.09	4.20	0.34
2305	-2.03	-1.17	-0.96	-0.84	-1.38	-1.77	- 1.12	- 9.27
October 1								
0005	-2.14	-1.22	-0.94	-0.75	-0.76	-0.95	2.80	- 2.06

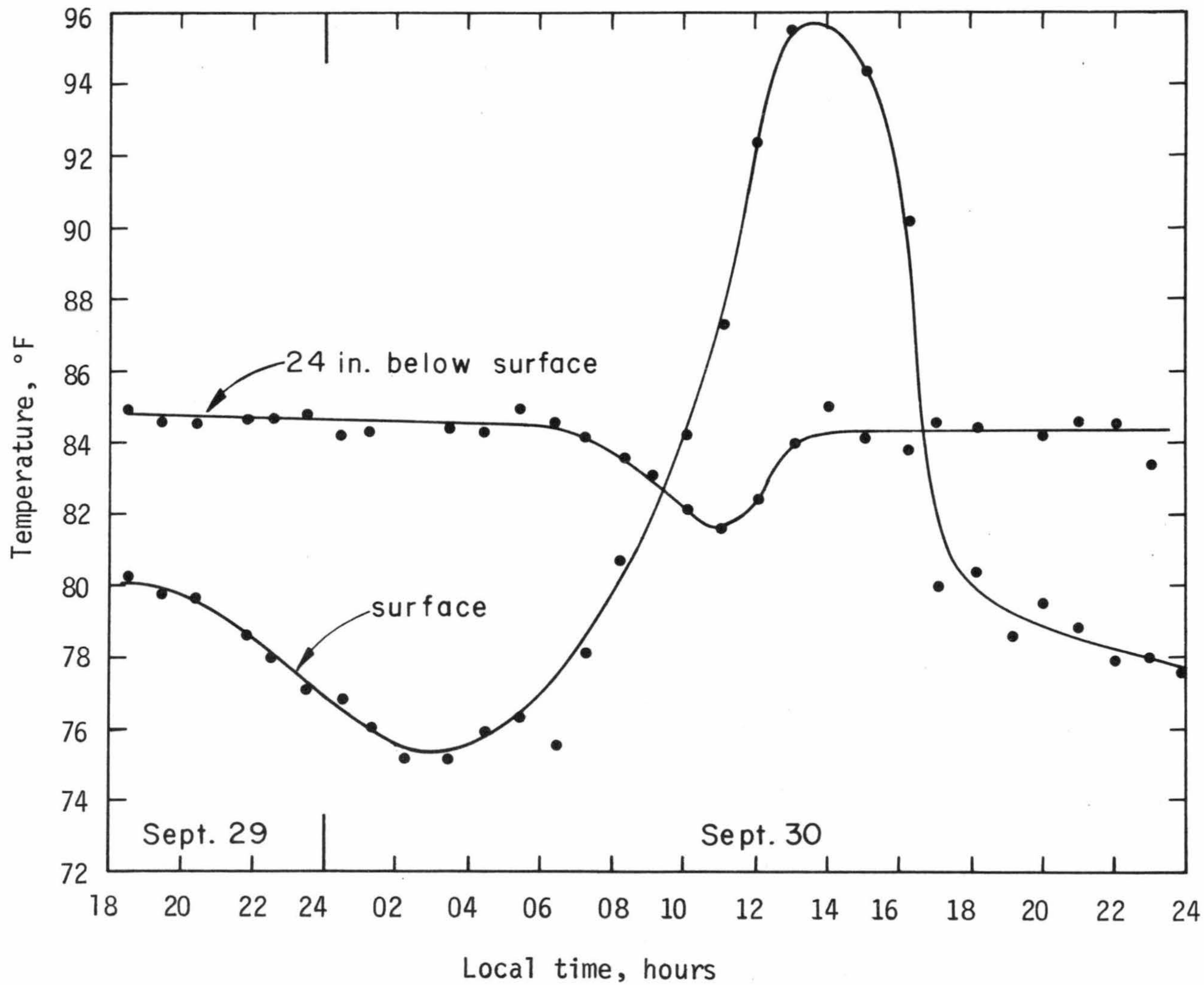

FIGURE IV-1 VARIATIONS OF SOIL TEMPERATURE WITH TIME

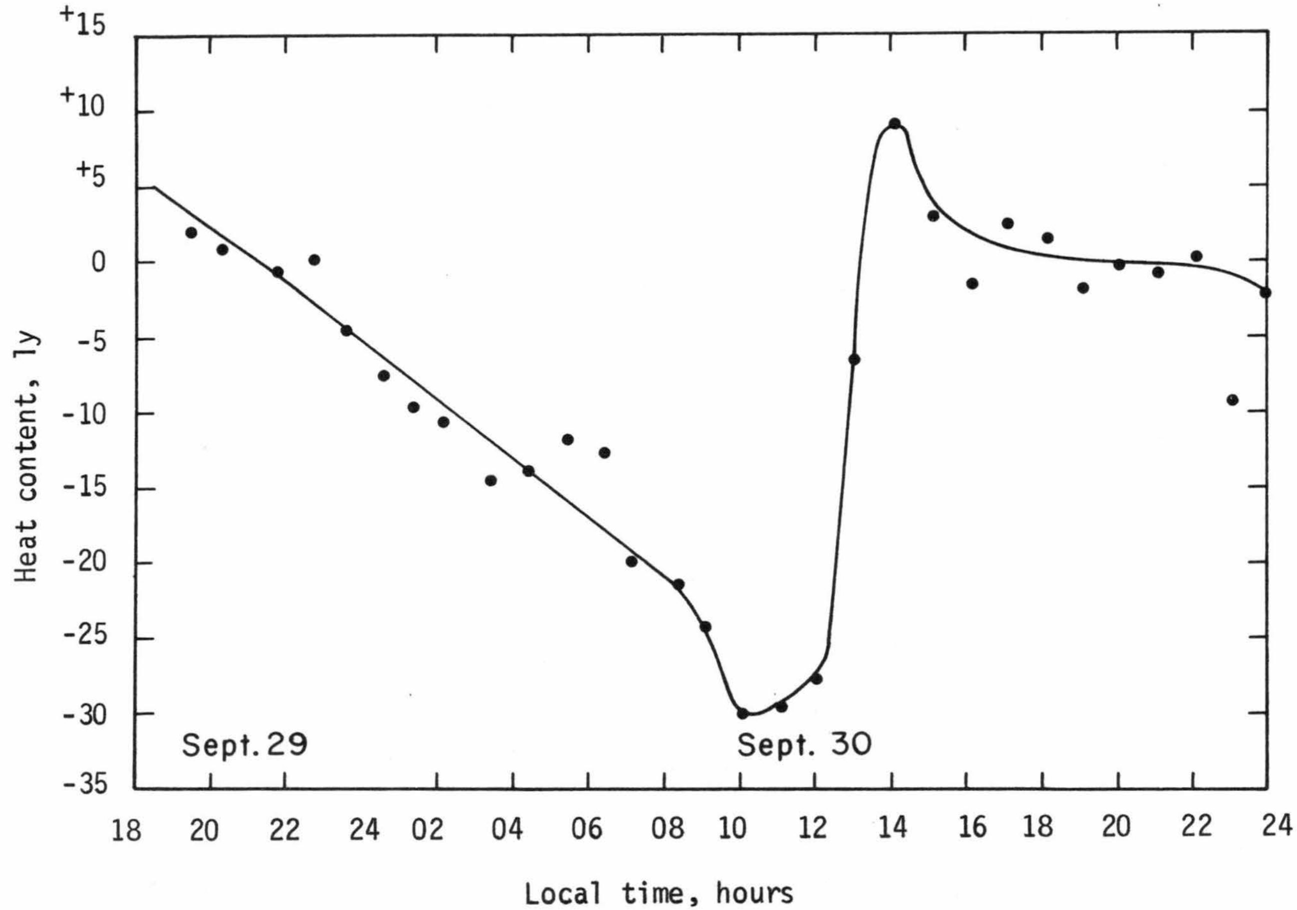

FIGURE IV-2 VARIATIONS OF SOIL HEAT CONTENT WITH TIME

CHAPTER V

CONCLUSIONS

1. At the Anaco raingage site, the top 24 inches of soil is normally compacted sand with a median diameter of 0.3 mm.

2. For sandy soil, the heat capacity per unit weight of soil, c_o, is approximated by the expression

$$c_o = 0.177 + m$$

where m is the moisture content.

3. The heat capacity per unit volume of soil, K, called the heat capacity factor, is the ratio of the change in heat content per unit volume to the change in bulk temperature. For the soil at the Anaco raingage site, K has the value of approximately 0.3 cal/cc/°C which is only 1/3 that of water. The sandy soil at the site is normally compacted and it was very dry during the study period.

4. Temperature variations in the soil at the Anaco raingage site during the study period (from 1800 hours on September 29 to 2400 hours on September 30, 1969) were large at the surface and in the top inch of soil. The surface temperature varied from 75°F at 0300 hours to 96°F at 1300 hours on September 30.

5. At a depth of 24 inches below the ground surface, the temperature remained essentially constant between 84°F and 85°F except for a 6-hour period when the temperature dropped to a minimum of 82°F (1100 hours on September 30) and then increased again to 84°F.

6. The heat content of the upper 24 inches of soil at the Anaco raingage site decreased steadily from 1800 hours on September 29 to a minimum at 1000 hours on September 30. The average rate of heat loss during this period was 2.2 ly/hr.

7. Between 1000 and 1400 hours on September 30, the heat content of the soil increased at an average rate of approximately 9 ly/hr. The maximum rate of increase was 22 ly/hr in the period between 1200 and 1300 hours.

8. From 1400 to 2400 hours on September 30, the heat content remained essentially unchanged.

9. The maximum rate of increase in soil thermal energy (22 ly/hr) in the period between 1200 and 1300 hours represents nearly 60 percent of the net incoming solar radiation reported by Renné (1970) for the same area.

10. The average rate of decrease in soil thermal energy during the night-time hours (2 ly/hr) agrees closely with the night-time long wave back radiation of 3 ly/hr reported by Renné (1970) for the same area.

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