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CONTENTS

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AN EXPERIMENT TO MEASURE THE ENERGY BALANCE OVER SHORT GRASS IN AN ORCHARD AT MONT ST. HILAIRE, QUEBEC

by

Atsumu Ohmura and R. F. Fuggle*

INTRODUCTION

During the period July 22-27, 1968 an experiment to measure the components of the energy balance over a short grass surface in the Mont St. Hilaire Climatological Station of the Department of Geography , McGill University, was organized. The station is situated in an apple orchard on the University's Gault Estate, 700 feet above sea level, and 500 feet above the surrounding St. Lawrence lowlands. The site is exposed to the south, but has hills to the east, north and west. However, the orchard itself is not untypical of many of the apple orchards in this part of Quebec.

A major objective of the experiment was to compare the results from different methods of surface energy balance measurement in an environment of this type. Other objectives included a comparison of the results obtained using different types of instruments, as well as an assesment of the frequency of observations required to obtain satisfactory results from non-recording instruments.

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(a)

(b)

Fig. 1. Radiation Measuring Instruments,
Mont St. Hilaire, Quebec. (Photos by Ravi Swami)

METHOD AND INSTRUMENTATION

The energy balance of a surface can be expressed in the following way:

$$R = G + LE + H \tag{1}$$

$$R = Q + q + r + L\downarrow + L\uparrow \tag{2}$$

where R is net radiation, G is heat conduction into or out of the surface, L is the latent heat of vaporization of water, E is evapotranspiration or condensation, H is sensible heat flux, Q is direct solar radiation, q is sky diffuse radiation, r is reflected short wave radiation, $L\downarrow$ is long wave incoming radiation and $L\uparrow$ is long wave outgoing radiation. Heat exchange due to precipitation was ignored in the above equations.

Net radiation (R) was measured by a Funk type net radiometer (a Swissteco Type E-1) installed at 150 cms above the ground, and ventilated by air (Fig. 1a). Out-put from the radiation sensor was recorded on a Leeds & Northrup speedomax H potentiometric recorder with an Azar module. The chart of this recorder is 6 ins. wide. During daylight hours a chart span of 100 mv was used, but by night an adjustment to a span of 10 mv and an apropriate zero displacement was made. A chart speed of 10" per hour was employed. Hourly values were obtained by planimetric integration of the resulting curves.

Global radiation (Q + q) was measured by a Kipp & Zonen pyranometer which was installed near the net radiometer (Fig. 1a). A down facing pyranometer of the same make measured short wave reflected radiation (r) from the grass surface. A third Kipp & Zonen pyranometer situated to the west of the other instruments, was protected from direct solar radiation by a shade-ring enabling sky diffuse radiation (q) to be recorded (Fig. 1b).

The temperature at the ground surface was measured by standard minimum thermometers resting on the surface, and also by copper-constantan thermocouples. Outgoing long wave radiation ($L\uparrow$) was calculated from these surface temperatures using the Stefan-Boltzman equation, and assuming a surface emissivity of 0.95, which is common among grass surfaces. (Sellers, 1965). Long wave incoming radiation ($L\downarrow$) was then calculated from Eq. (2) as a residual of the other measured radiation values.

Soil heat flux was measured continuously at 5 mm below the ground surface by means of a Thornthwaite model soil heat flux recording system, using a single soil heat flux plate. This recording system operates at a chart speed of 1" per hour with a 6.8 mv full scale deflection over a chart width of 2.35 ins. However, this system did not provide a sensitivity equivalent to that of the net radiometer.

LE and H are always difficult terms to measure in the energy budget. In the present study these terms were estimated by means of the Bowen ratio, (Bowen, 1926; Thornthwaite and Hare, 1965). The Thornthwaite-Holzman relationship (Thornthwaite and Holzmann, 1939; idem 1942), and by the direct measurement of evapotranspiration using a weighing lysimeter (Fig. 2).

The following two equations were used for calculations by the Bowen ratio:

$$LE = \frac{R - G}{1 + \frac{C_p}{L}\frac{\Delta T}{\Delta q}} \tag{3}$$

$$H = R - G - LE \tag{4}$$

For the Thornthwaite-Holzman relationship, the following equations were used:

Equations (5) and (6) on p.5 of Climat. Bulln. No.4, July 1968, should be amended to read:

$$LE = - L\rho k^2 \frac{(q_1 - q_2)(u_2 - u_1)}{(\ln z_2/z_1)^2} \tag{5}$$

and $$H = - Cp\rho k^2 \frac{(T_1 - T_2)(u_2 - u_1)}{(\ln z_2/z_1)^2} \tag{6}$$

In these equations, C_p is specific heat of the atmosphere at constant pressure, T is air temperature, q is specific humidity, ρ is the density of the atmosphere, z is the height above the surface, and k is von Karman's constant, taken as k = 0.4 (Huschke, 1959).

The use of the Bowen ratio requires the measurement of temperature and humidity at two levels, while the Thornthwaite-Holzman relationship requires not only temperature and humidity at two levels, but wind speed as well. The levels chosen in both cases during the present experiment were 150 cms and 10 cms.

Three different instruments were used for temperature and moisture measurements: precision thermistors, Assmann psychrometers, and standard bi-metallic thermographs and hair hygrographs.

The thermistor system consisted of two wet-bulb and two dry-bulb thermistors operating in a single bridge circuit powered by a 6 v battery. The four thermistors were mounted at two levels as shown in Fig. 3, the wet bulbs being fed from a plastic reservoir into which

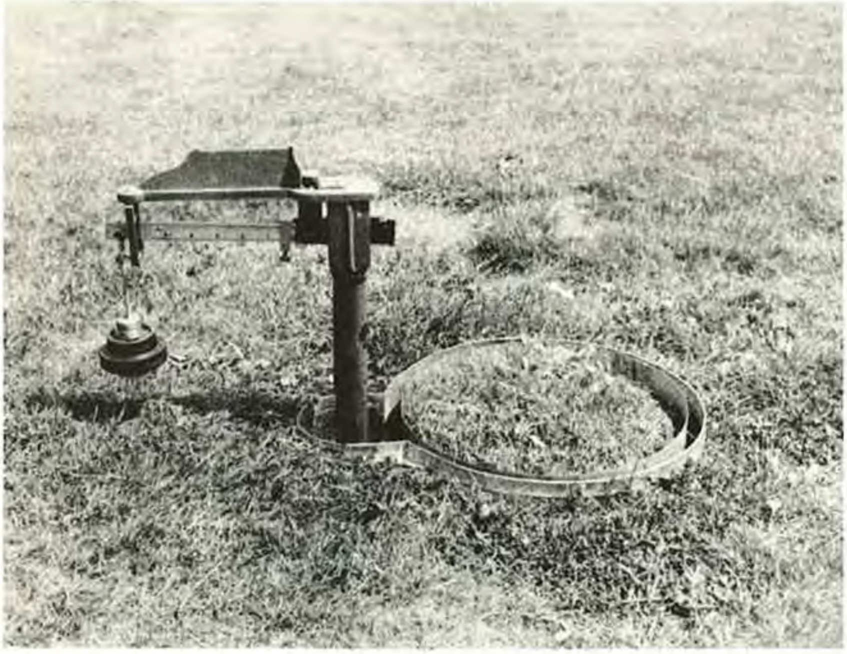


Fig. 2. Weighing Lysimeter

Fig. 3. Two-Level Wet and Dry Bulb Thermistor System

Fig. 4. Wet Bulb Thermistor Wetting System

All photos by Ravi Swami

there was a long feed-wick (Fig. 4). All four thermistors were automatically and sequentially connected to the bridge circuit by a stepping switch the temperature records being produced on a pressure-sensing chart. The recorder has four temperature ranges: $-30^{\circ}F$ to $20^{\circ}F$; $0^{\circ}F$ to $50^{\circ}F$; $30^{\circ}F$ to $80^{\circ}F$; $50^{\circ}F$ to $100^{\circ}F$. The range is selected by a rotary switch. The system, designed by Thornthwaite Associates, operates on 12 v DC and was found accurate to $\pm 0.2^{\circ}F$, the four sensors being sampled over a period of five minutes. Two standard Assmann psychrometers were also used at the same levels, while two Short & Mason bimetallic thermographs and two Negretti & Zambra hair hygrographs were set in screens at the same height as the other instruments. The Assmann psychrometers were found to be accurate to $\pm 0.1^{\circ}F$, while the thermographs and the hygrographs could be read reliably to the nearest whole number.

Evapotranspiration was measured by means of a weighing lysimeter developed originally to measure daily totals, but nevertheless used in this experiment for hourly measurements. The instrument consists of a steel drum with a diameter of 44.0 cms. and a depth of 40.0 cms., containing a soil monolith weighing about 170 lbs. The drum is set on a standard commercial balance capable of accepting 250 lbs., and weighing to an accuracy of 0.5 oz. The latter weight represents a weight of water which, when evaporated, is equivalent to a latent heat flux of 5.5 calories for the size of drum used. This degree of accuracy is thought to be adequate for the daily totals for which the lysimeter is really designed, but is clearly inadequate for the needs of hourly observations. The whole apparatus is set in the ground so that the surface inside the drum is level with that of the

MONT ST. HILAIRE - HOURLY FIELD SHEET 1

MONTH________ DAY________ HOUR________ E.S.T. OBSERVER________

PRESENT WEATHER:

CLOUD: AMOUNT
TYPE
HORIZONTAL VISIBILITY
PRECIPITATION TYPE

WEATHER PAST HOUR:

WIND SPEED	READING	CONVERSION	GROUND SURFACE	READING	CONVERSION
(A) 150 CM BEFORE			TEMP. (A)	F	C
AFTER 120 SEC			(B)	F	C
DIFF		M.SEC.	(C)	F	C
(B) 10 CM BEFORE			SUM		C
AFTER 120 SEC			MEAN		C
DIFF		M.SEC.	PRECIPITATION	IN	MM
SOIL MOISTURE	M.A.	G.CM^{-3}	LYSIMETER:	LB OZ	
(A) 1 CM			LAST HOUR		
(B) 5 CM			THIS HOUR		
(C) 10 CM			DIFF		MM
(D) 50 CM			ATMOMETER: CC EAST		
(E) 90 CM			WEST		
ASSMANN (A) 150 CM DRY			SUM		
WET			MEAN		
(B) 10 CM DRY			C.B. EVAPO. CC		
WET					

MONT ST. HILAIRE - HOURLY FIELD SHEET 2

MONTH________ DAY________ HOUR________ E.S.T. OBSERVER________

POTENTIOMETER READINGS

	READING	CONVERSION	SOIL TEMPERATURE	READING	CONVERSION
TEMP. OF METAL COVER	F	C	MEASURES 1 CM	F	C
MERCURY THERMOMETER ON COVER	F	C	5 CM	F	C
THERMO-COUPLE ON METAL COVER	MV	C	10 CM	F	C
HEMISPHERE NET RADIATION	MV	C	20 CM	F	C
SOIL SURFACE TEMP. (A)	MV	C	50 CM	F	C
(B)	MV	C	85 CM	F	C
(C)	MV	C			
SUM					
MEAN		C			
SOIL HEAT FLUX PLATES: SURFACE	MV	LY.HR			
3 CM	MV	LY.HR			
8 CM	MV	LY.HR			
15 CM	MV	LY.HR			
30 CM	MV	LY.HR			

CHART ANALYSES

(A) NET RADIATION ________ LY.HR
(B) GLOBAL RADIATION ________ LY.HR
(C) SKY-DIFFUSE " ________ LY.HR
(D) REFLECTED " ________ LY.HR
(E) SOIL HEAT FLUX ________ LY.HR

COMMENTS:

Fig. 5. Field Sheets used during Energy Budget Experiment

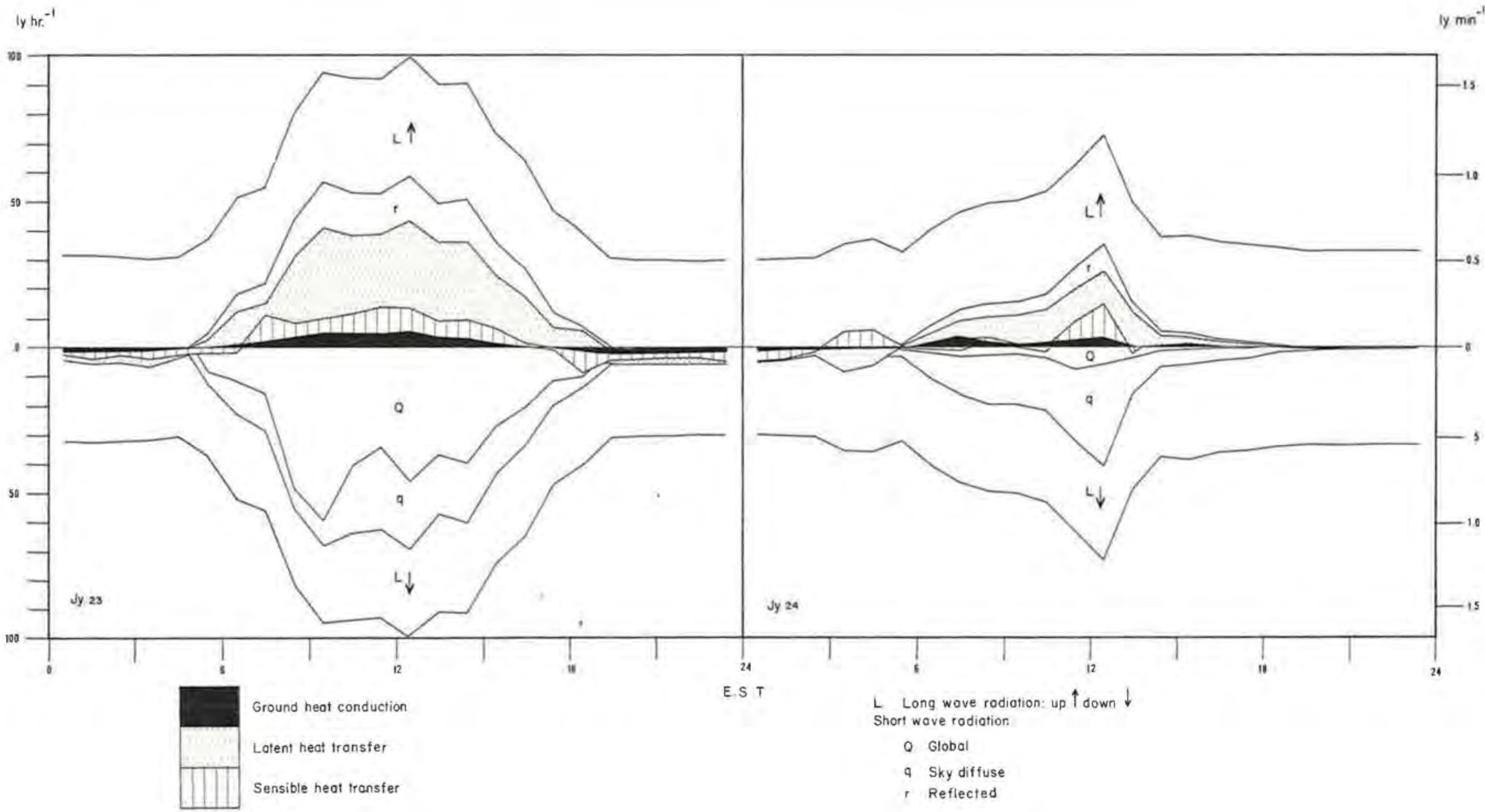
surroundings (Fig. 2). The bottom of the drum has a hole through which excess water drains. This water flows through a pipe into a run-off collector installed 1.5 meters away from the drum. The collector and its contents are weighed together with the drum each time an observation is made. The change of weight between two successive observations represents the evapotranspiration, due allowance being made for any rainfall.

In order to have hourly observations from the non-recording instruments, a team of five persons worked 4 to 6 hours shifts. The time of observation chosen was at the half-hour beginning at 1330 hrs. EST on July 22 and ending at 1730 hrs. EST on July 27. However, since a complete sequence of observations required at least twenty minutes, each person started his observation period ten minutes before the observation time so that he could finish ten minutes after the time. A sample of the field sheets used is shown in Fig. 5. The sheets were designed so that each observer followed an identical sequence of observations so that the time interval for the observation of a given instrument was always one hour.

RESULTS

The components of equations (1) and (2) for the period of observation are shown in Fig. 6, and the daily totals of each component as obtained by the Bowen ratio and lysimeter methods are shown in Table One.

For the 124 hours of observation, the largest total of absolute value was found in $L\uparrow$ (-4242 cal. cm^{-2}) which is compensated for by $L\downarrow$ (3513 cal. cm^{-2}) to make the net long-wave radiation for the


ly hr.$^{-1}$
ly min^{-1}
L↑
r
Q
q
L↓
Jy 23
Jy 24
E.S.T.
Ground heat conduction
Latent heat transfer
Sensible heat transfer
L Long wave radiation: up ↑ down ↓
Short wave radiation
Q Global
q Sky diffuse
r Reflected

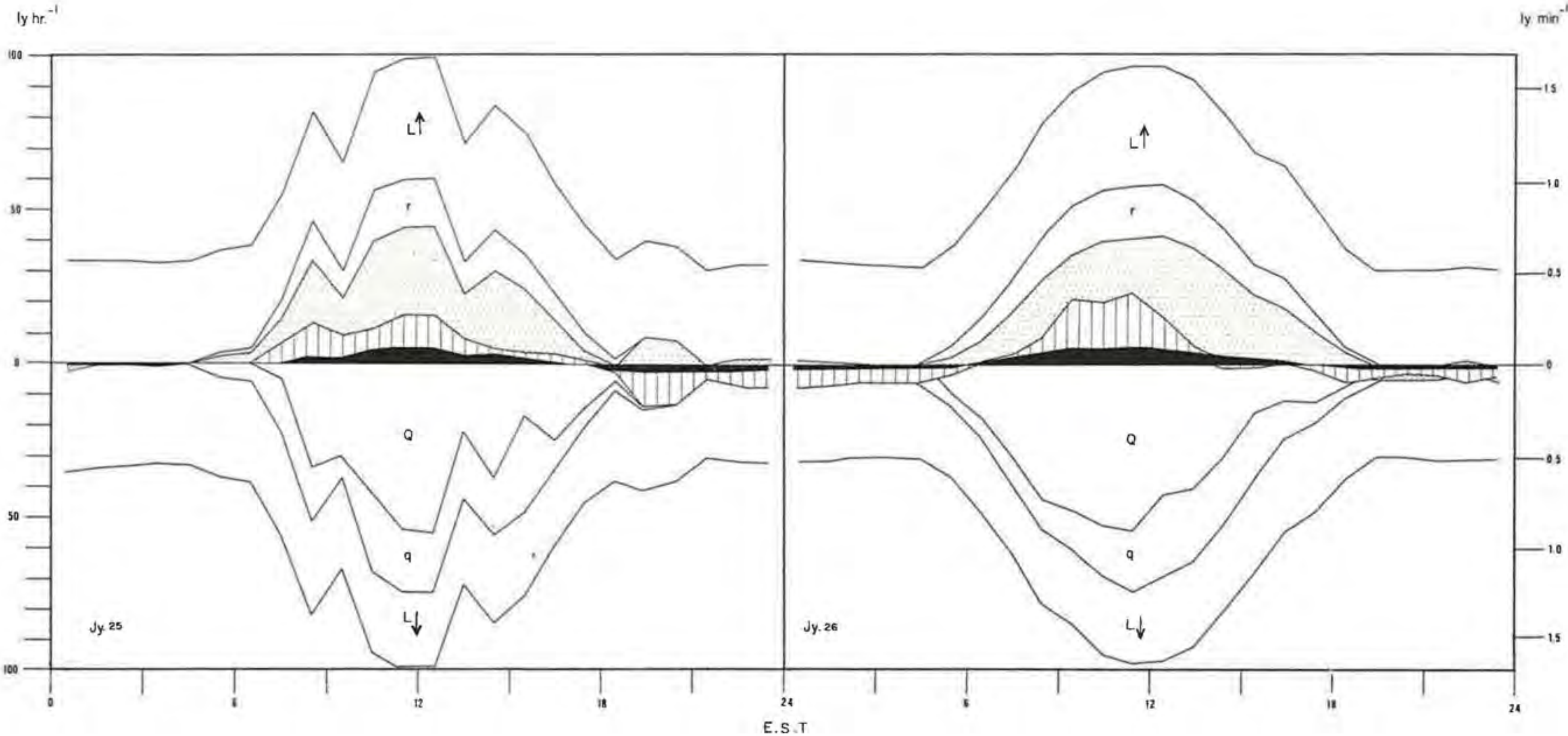


Fig. 6. The Energy Balance at Mont St. Hilaire, Quebec, July 23 - 26, 1968

TABLE ONE

DAILY TOTALS OF ENERGY BALANCE COMPONENTS,
MONT ST. HILAIRE, JULY 22-27

($cal.cm^{-2}$)

July	Q	q	r	L↑	L↓	R	$LE^{(1)}$	$H^{(1)}$	$LE^{(2)}$	$H^{(2)}$	G
22*	148	71	51	390	350	128	155	-34	149	- 28	8
23	393	202	145	823	662	289	238	29	195	71	23
24	28	167	47	794	734	88	101	-22	128	- 50	10
25	316	230	130	832	686	264	224	27	169	81	15
26	422	196	155	814	614	263	228	25	216	36	12
27**	247	201	109	588	467	223	186	22	134	75	18
Total for period	1554	1067	637	4242	3513	1255	1132	47	991	185	85

* 11 hours of measurement

** 17 hours of measurement

(1) Calculated by the Bowen ratio using the results from Assmann psychrometers

(2) Calculated from lysimeter measurements.

period equal to -729 $cal.cm^{-2}$. Incoming global radiation totalled 2621 $cal.cm^{-2}$ of which 59% was received as direct short-wave radiation and the remainder as sky diffuse radiation. The reflected short-wave radiation amounted to 637 $cal.cm^{-2}$. This makes the mean albedo of the period 24.3%, a figure which is within the range of values for grass surfaces given in the Smithsonian Meteorological tables (List 1963). Over the

124 hour period the surface received 1255 cal. cm^{-2} as net radiation. This amount can be taken as the heat source for evaporation, heat conduction into the ground, and for warming of the atmosphere. Analysis shows that about 7% of this total was used to heat the ground. The Bowen ratio calculations indicated that 89% was used in evaporation and 4% was used for sensible heat flux. However, results calculated from the lysimeter measurements indicated that 78% was used for evaporation and 15% as sensible heat flux.

A summary of the 124 hours of observations shows the following totals (calculated to the first decimal place on an hourly basis but summed to the nearest whole number): net radiation = 1255 cal.cm^{-2} and soil heat flux = 85 cal. cm^{-2}. The latent and sensible heat fluxes calculated by using the Bowen ratio were 1132 cal.cm^{-2} and 46 cal.cm^{-2} respectively. The latent and sensible heat fluxes by the energy balance equation (Eq. 1) using the lysimeter measurements were 991 cal. cm^{-2} and 185 cal. cm^{-2} respectively. In spite of these different totals, the values obtained from the Bowen ratio and the lysimeter measurements parallel each other in diurnal trends. By contrast the same two terms calculated by the Thornwaite-Holzman formula are 393 cal. cm^{-2} and -68 cal. cm^{-2} respectively, results which are not only different from those of the previous methods but which also fail to balance Eq. (1) by some 855 cal. cm^{-2}.

The general pattern of the diurnal change of soil heat flux, latent heat flux, and sensible heat flux are very variable due to the weather conditions. However, the fluctuations between day and night are so well marked that some general trends could be deduced. Soil heat flux and latent heat flux showed positive values as soon as the sun rose

(0500 hrs. EST), while sensible heat flux remained negative for about an hour after sunrise, after which it became positive. Both the latent heat flux and the net radiation increased to a maximum round about noon. On the other hand, soil heat flux increased rapidly as the ground warmed so that its maximum was attained in the late morning. The sensible heat flux appears to be very variable, partly no doubt because of advection influences, but also because of inadequate direct methods for determining this flux. Therefore, the sensible heat flux term may be accumulating the errors of the other terms. Nevertheless, it is apparent that the sensible heat flux changed from negative to positive a short time after sunrise, reached its maximum in the late morning like the soil heat flux, and became negative again in the early afternoon, earlier than the other fluxes.

Although, the latent heat flux calculated by the Bowen ratio approximates that calculated from lysimeter measurements even at an hourly level, some problems exist in each case. In particular, the Bowen ratio gives very odd values, and in fact fails to function when H/LE becomes close to -1. This occurs fairly frequently just after sunrise and before sunset, so that it appears advisable to interpolate values for these hours from the previous and subsequent values. As far as the results based on lysimeter measurements are concerned, they must inevitably be to the nearest 5 cal. cm^{-2} owing to the limitations of the instrument. This is why the latent heat flux by this method is either zero or 5 cal. cm^{-2} at night.

The results calculated by the Thornthwaite-Holzman relationship were disappointing. Although this method gives similar results to the others at night, the values during the day become one-half to one-third of the values calculated by the other methods. As a result, this method must be considered an unsuitable way of calculating the energy balance under the conditions and site of the experiment. The reason probably lies in the presence of hills and trees around the station. This greatly disturbs the wind profile, which should be logarithmic for the proper use of this method of calculation.

It is apparent from the foregoing discussion that the calculation of both latent and sensible heat flux by means of the Bowen ratio provides reasonable results under the conditions of the experiment. Some comparison of the results achieved by this method using data from different instruments and observation intervals may therefore be interesting.

The three methods used to measure the temperature and humidity profiles can all be used for calculations by the Bowen ratio. The results of calculating latent and sensible heat flux on the basis of hourly observations using each of these methods are illustrated for one day (July 26) in fig. 7. Of the instruments used, Assmann psychrometers are the most tested and reliable, and could accordingly be expected to give the best results. In practice this did not always occur because of human observational errors. Misreading was particularly apparent at night. If a misreading is not noticed by an observer at once, either by double or triple checking, or by cross checking with another instrument or some other means, the reading is completely lost. On a recording instrument, however, even if it is no more than a pen on a clockwork drum, it is often possible to make reasonable corrections for some temporary instrumental aberration. Such corrections cannot be

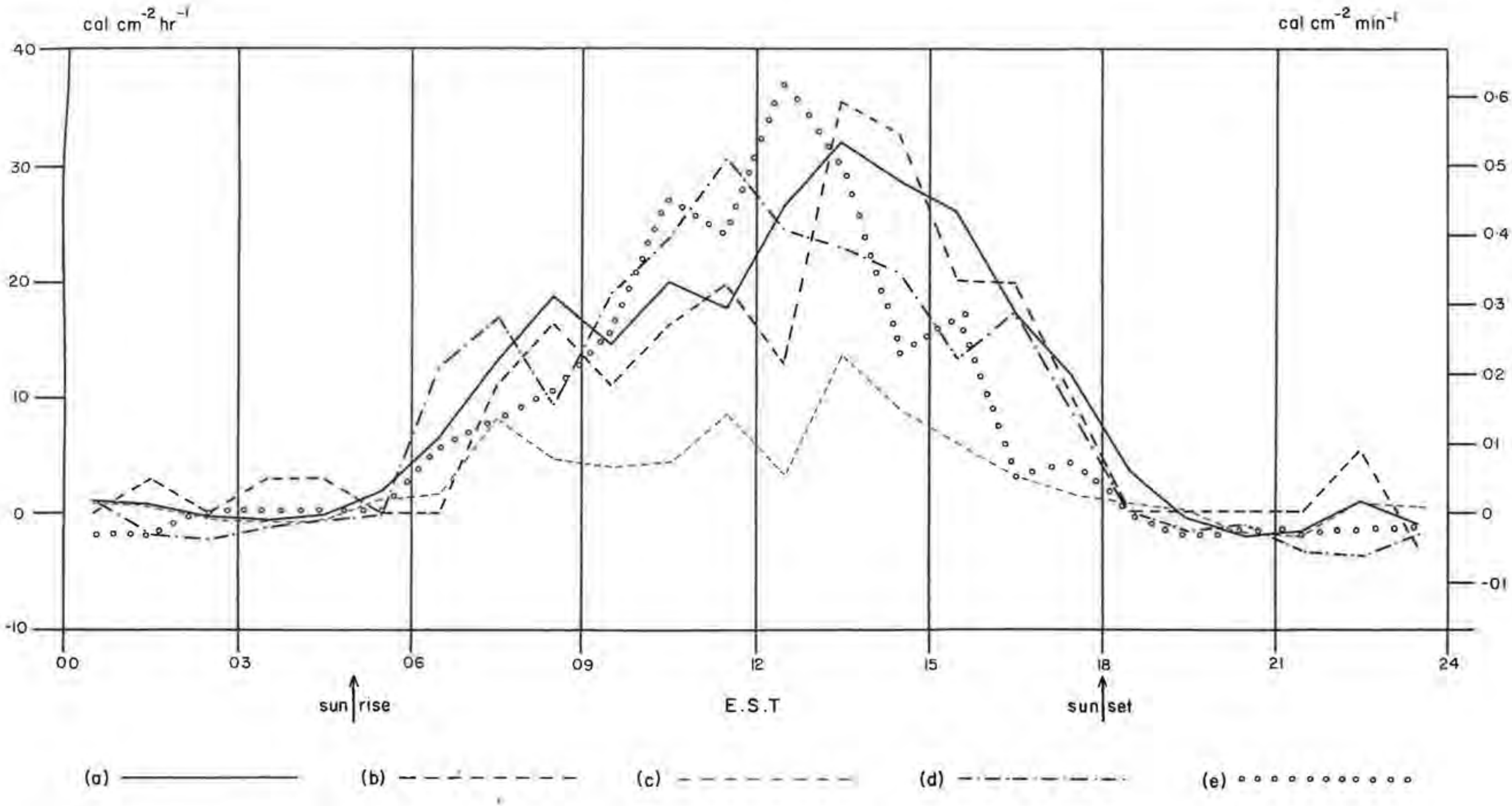


Fig. 7. The Latent Heat Flux at Mont St. Hilaire, Quebec, for July 26, 1968, calculated by different methods: using Bowen ratio calculated from (a) Assmann psychrometer observations, (d) recording thermistors, (e) thermographs and hair hygrographs at two levels; (b) using the energy balance equation and weighing lysimeter observations; (c) using Thornthwaite-Holzmann equation.

made for a misread Assmann psychrometer. Thus, during the experiment described in this article, the results of calculations from Assmann psychrometer readings were frequently less satisfactory than from the other two instrument sources.

Calculation of latent heat flux and sensible heat flux from the thermistor temperature recording system gave consistently steady results. They provide a smoother curve when graphed and also come quite close to the results achieved by means of the weighing lysimeter.

The results achieved by calculations from the data of the bimetallic thermographs and hair hygrographs were rather better than expected. These instruments are not intended for precision work but they are cheap and easy to operate. They were carefully calibrated and checked for a week in the Stevenson screens at the station. The two fluxes calculated from the data are very close to those obtained by the other instruments. It would seem possible, therefore, to use this form of instrumentation in terms of daily values or longer periods. The minor heat flow, especially near sunrise and sunset is not however indicated by these instruments.

The final point of interest is to compare the effect of calculating these fluxes on the basis of observations at different time intervals. The calculations based on the data obtained every one hour, two hours, three hours and six hours are shown in Table Two. Reference to this table suggests that reasonable estimates of daily totals could be obtained from observations taken every three hours in the absence of more detailed data, but that a six-hour period gives estimates rather far from the daily totals calculated on an hourly basis.

TABLE TWO

VALUES OF LATENT AND SENSIBLE HEAT FLUXES BASED ON CALCULATIONS MADE AT DIFFERENT TIME INTERVALS

($cal.cm^{-2}day^{-1}$)

Totals calculated from every	Jul.23		24		25		26	
	LE	H	LE	H	LE	H	LE	H
" " 1 hr.	238	29	101	- 22	224	27	228	25
" " 2 hr.	252	15	95	- 16	222	29	236	13
" " 3 hr.	253	14	136	- 57	205	46	224	29
" " 6 hr.	298	-31	229	-150	194	57	246	3

CONCLUSION

The Bowen ratio and the energy balance method using a lysimeter gave generally similar results both in terms of diurnal trends and absolute values, while the Thornthwaite-Holzman equations underestimated the latent and sensible fluxes considerably. The experiment could not make good use of the accuracy of Assmann psychrometers because of human errors which were particularly apparent at night readings. Although the thermistors were not ventilated, their results were reasonably good. The bimetallic thermographs and hair hygrographs yielded unexpectedly good results although they are not accurate enough to give reasonable diurnal fluctuations. An observation every three hours appears to be the maximum time interval for reading non-recording instruments.
The experiment seems to have provided useful answers to the objectives stated in the introduction to this article. However, out of the experience of the present experiment, the following suggestions are made for improved observations during a second experiment, at present planned for October, 1968:

(a) The net radiometer should be ventilated by nitrogen.

(b) As mentioned in the section on method and instrumentation, the sensitivity of the soil heat flux recording system was inadequate to balance that of the net radiometer. To rectify this the sensitivity of the soil heat flux system should be at least three times as large as that used in the present experiment. This may be achieved either by increasing the output of the sensor or by amplifying the output. This increased sensitivity is especially important close to the times of sunrise and sunset when the magnitude of G is equivalent to that of net radiation. At this time, therefore, the direction of the sign of (R - G) is dependent on minor heat flux values which in turn significantly influence the direction of the sign of latent and sensible heat fluxes.

(c) The thermistors should be ventilated. With an unventilated system the difference between the lower and upper wet-blub readings is badly distorted owing to the greater air movement naturally occurring at the higher elevation. Moreover, ventilation will mean that the conditions of operating the automatic system will come much closer to those for operating the Assmann psychrometers. The latter can then be read less frequently and relied on only as checks.

(d) In the present experiment the heat storage between the soil heat flux plate and ground surface was not taken into account, However, this storage is not inconsiderable, particularly in the early morning when this layer is quickly warmed. It is, therefore, desirable to measure the temperature within this layer by thermocouples and to calculate the heat storage by reference to soil heat capacity.

ACKNOWLEDGEMENTS

The experiment described in this article was organized and supervised by the writers of the article. They were assisted by Brian Banks, Noel Pelletier, and Ravi Swami.

REFERENCES

Bowen, I. S., 1926: "The ratio of heat losses by conduction and by evaporation from any water surface," Phys. Rev., 27, pp.779-787.

Huscke, Ralph E. (ed.), 1959: Glossary of Meteorology, Am.Meteor.Soc. Boston, 638 pp.

List, Robert J., 1963: "Smithsonian Meteorological Tables," Smith.Misc.Coll. Vol. 114, 6th ed., 527 pp.

Sellers, William D., 1965: Physical Climatology, Univ. of Chicago Press, 272 pp.

Thornthwaite C. Warren & F. Kenneth Hare, 1965,: "The Loss of Water to the Air," Meteor. Monographs, Vol. 6, No. 28, pp. 163-180.

Thornthwaite C. W. & B. Holzmann, 1939: "The Determination of Evaporation from Land & Water Surfaces", Monthly Wea. Rev., 67. pp. 4-11.

__________, 1942: "Measurement of Evaporation from Land & Water Surfaces," U. S. Dept. Agric. Tech. Bull'n. No. 817, 75 pp.

TWO MAPS OF DIRECT SHORT-WAVE RADIATION IN BARBADOS

by

B. K. Basnayake*

Recent work in the climatology unit of McGill University has resulted in the development of a formula which can be used to map the distribution of direct short-wave radiation income over a given area from the observations of a single, representative site. The theory, limits of accuracy, and method of using the formula, the essential elements of which are given at the end of this article, are available elsewhere (Ohmura, 1968; Garnier & Ohmura, 1968) and need not be repeated here. The purpose of the present article is to provide a preliminary report on the effect of applying the formula in Barbados on two days, one near each of the solstices.

In order to apply the formula for radiation mapping it is necessary to prepare appropriate tables for the latitude in question and also a base map for the area being studied. The former is a simple matter involving only the insertion of appropriate values in an already-prepared computer programme. The latter, however, is more complex, it being necessary to devise a base map appropriate to the nature of the local relief and the degree of detail required in the results.

Base map preparation involves making a grid, at each intersection of which are marked the slope angle and azimuth. It is important that the closeness of this grid should be related to the intensity of the

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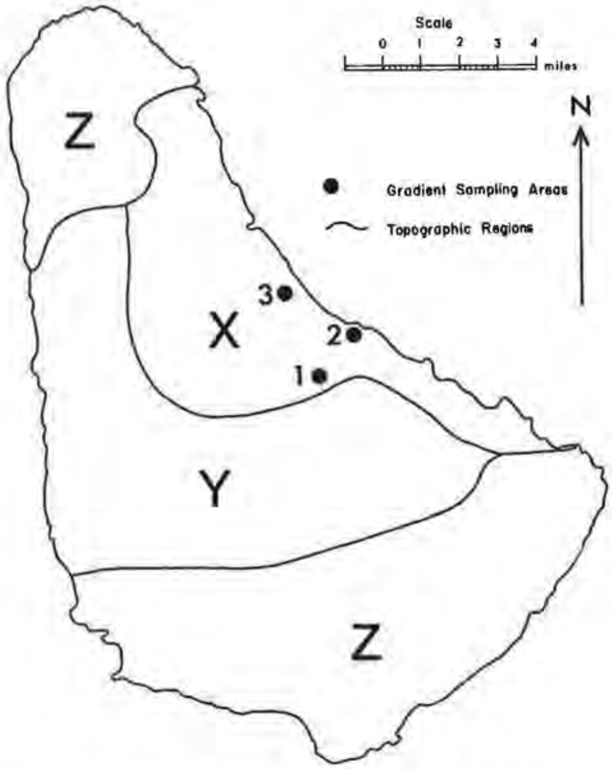

Fig. 1. Regions of Barbados for relief sampling: X 2.5 cm. squares, Y 5 cm. squares, Z 10 cm. squares (See text.)

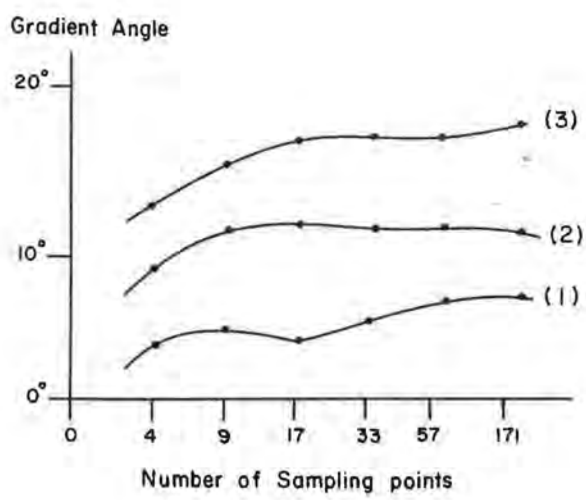

Fig. 2. Sampling Points and Gradient Angles.
(Bracketed numbers refer to the gradient sampling areas in Fig. 1)

relief of the area. The base map used for the radiation maps of Barbados was prepared from the 1:10,000 topographic map series (18 sheets) prepared by British Colonial Surveys in 1953. These map sheets already have on them a basic grid, 10 cm square. Using the intersections of this grid as sampling points appeared to be adequate for the southern part of the island with its gently rolling topography, but seemed quite inadequate for the hilly central and eastern parts. The maximum density of sampling points required in these more hilly areas, therefore, was determined as follows: three 10 cm squares of varying types of complicated relief were selected (Fig. 1), and the average gradient was calculated for each, using successively, doubled numbers of sampling points. The results are shown in Fig. 2. The gradient averages reached stable values at between 17 & 33 points per 10 cm square. Therefore the figure of 25 points per 10 cm square was adopted, giving a grid pattern of 2.5 cm squares, for the areas with the most complicated relief in the island. The same method was used to determine the sampling density required for areas of intermediate relief, and a grid 5 cm square was adopted for this part of the island. Thus, it was possible to divide the island into the regions shown in Fig. 1 using the different grid pattern densities calculated. In order to measure slope gradient it was decided to use the number of successive contour lines for a standard distance, rather than the distance between individual adjacent contours. This procedure was adopted for two reasons: because of the difficulty of accurately measuring small distances between contours, compared with the ease of counting successive contours within a comparatively large pre-determined standard space, thus entailing little loss of accuracy of the final figure; and because the use of a standard space for gradient measurement allows one to get an average value that takes into account the area round a sampling point, rather than the value of a single point. A circle 15 mm in diameter was used for gradient measurement. This size was chosen to avoid both the amibguity of single contour interpretation as would often be met with when using a smaller circle, and the difficulty of visually determining average slope direction and counting too many contours if the circle were large.

The 1:10,000 maps used as base maps have contours drawn on them at 20 ft intervals. For such a map, therefore, the number of contours in a 15 mm distance corresponding to different angles of slopes is given by the equation

$$y = \frac{15 \tan x}{.610} \qquad (1)$$

where x is the given slope angle, and y the number of contour crossings in 15 mm of map distance.

For slope and azimuth analysis a standard clear plastic protractor was modified in order that it could measure both slope direction and gradient in a single step. A movable pointer of semi-rigid clear plastic was pivoted at the origin of the protractor. The pointer was marked with a central longitudinal line, together with another line perpendicular to it and passing through the pivoted origin. A circle of 15 mm diameter with its centre at the pivoted origin was also marked on the pointer. For use, the protractor with pointer was placed with its origin on the selected grid intersection of the topographic map. To obtain slope direction, the pointer was moved so that its marker line was perpendicular to the major contour trend, and the angle read off on the circular margin of the protractor. For gradient angle, the number of successive contours within the circle marked on the pointer was counted, and the corresponding gradient value obtained from a table prepared from eq. (1).

In gradient measurement, great care was taken to ensure that the contour lines counted were truly successive, and not repeating the same values, as for example, in the case of those doubling back on themselves, for serious errors would otherwise ensue. In the case of open valleys or spurs, slope measurement was done on the main axis. Narrow deep valleys, a large number of which exist in the limestone topography of Barbados, were ignored in the slope analysis, because they were considered to play an insignificant role in the regional picture, and especially because, on inspection, many of them seem to be choked with bushes and trees, so that the effective surface was often level with the adjacent plateau and sometimes even higher.

The radiation data for the maps were obtained from records maintained during 1964 by D.G. Tout (Tout, 1968). The total direct short wave radiation on December 28 of the year was 436 langleys and on June 18 it was 438 langleys. Reference to tables prepared for latitude 13°N (the latitude of Barbados) shows that these data imply a mean atmospheric transimisivity of 0.75 and 0.55 respectively for these two dates. Consequently the values for different slopes and azimuths as given in Table One were used in preparing the maps. The final results are shown in Figs. 3 and 4 respectively.

The June map (Fig. 3) shows comparatively little topographic variation. The extreme range being between 440 and 350 langleys, assuming

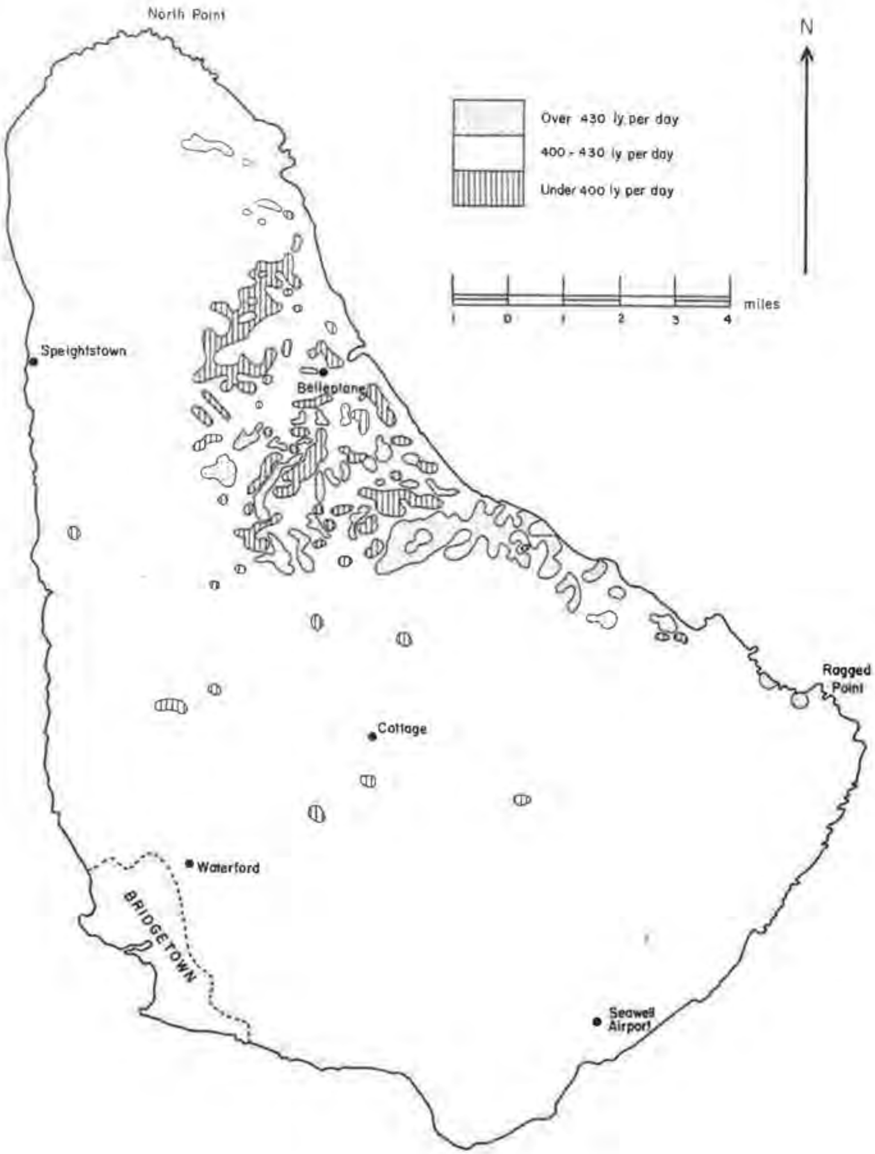

Fig. 3. Variations of Direct Solar Radiation over Barbados, June 18, 1964

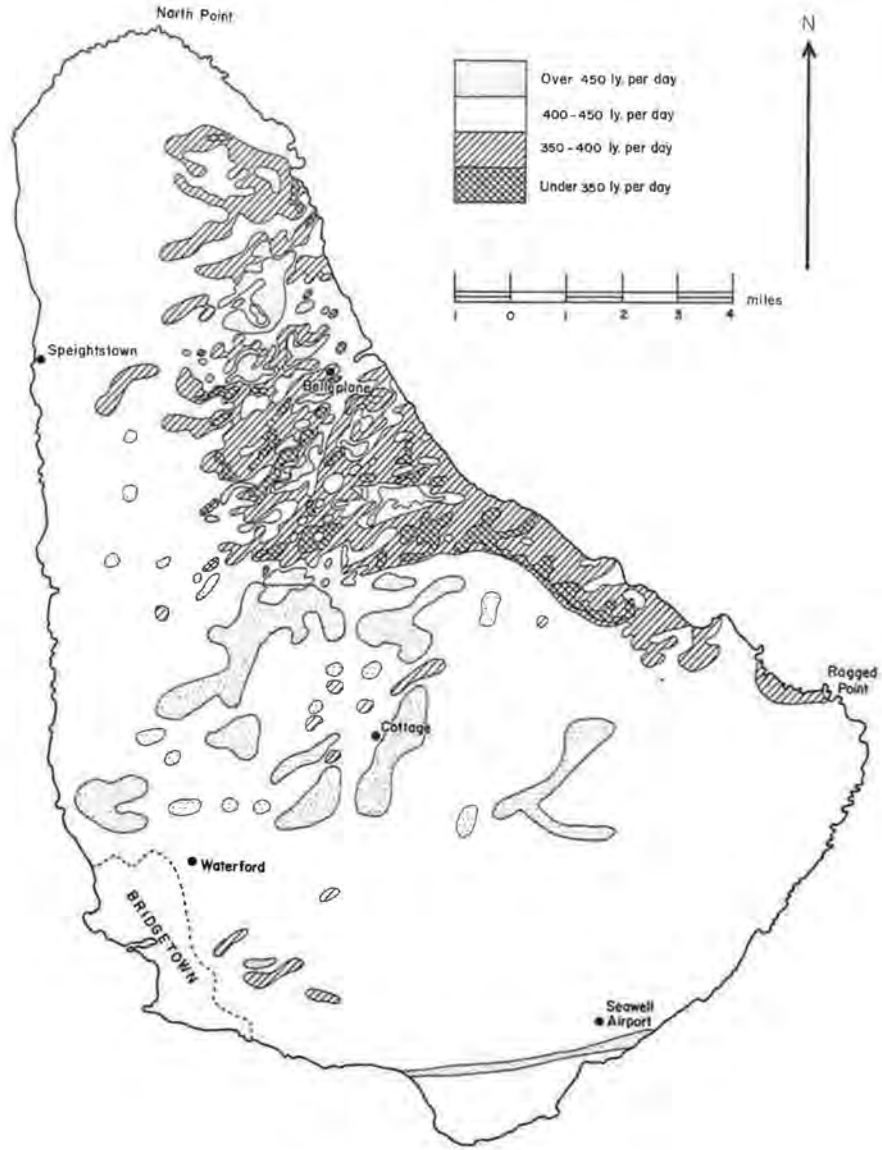

Fig. 4. Variations of Direct Solar Radiation over Barbados, December 28, 1964

a mean level surface value of 420 ly. The map for December 28 (Fig. 4), shows much greater contrast. The maximum and minimum values give a range of approximately 285 ly, compared to the summer range of only 80 langleys. Yet the horizontal surface value of direct radiation was virtually equal on both dates. Thus, the maps suggest that even in the tropics, topographic variation of insolation is significant for at least part of the year. They demonstrate, in addition, the considerable degree of resolution in areal differentiation achieved by this method for an important element of the total surface radiation balance. Further evaluation of the use of the method in surface radiation balance studies is at present being undertaken as part of a programme of energy balance research in Barbados.

TABLE ONE

VARIATION OF DAILY DIRECT SOLAR RADIATION FOR DIFFERENT SLOPES AND AZIMUTHS

(in langleys)

	Winter Solstice P = 0.75 Slope Angle				Summer Solstice P = 0.55 Slope Angle			
Azimuth	0	10	20	30	0	10	20	30
0	423	351	268	179	420	435	436	424
10	423	352	270	183	420	434	435	423
20	423	355	277	195	420	433	434	421
30	423	359	287	212	420	432	431	416
40	423	366	301	233	420	430	426	410
50	423	374	317	258	420	427	421	403
60	423	384	336	285	420	424	415	395
70	423	394	356	314	420	421	409	386
80	423	405	378	344	420	417	402	376
90	423	416	399	375	420	413	395	367
100	423	428	421	405	420	410	388	357
110	423	439	442	434	420	406	381	347
120	423	449	462	462	420	403	374	337
130	423	459	480	488	420	400	368	327
140	423	467	496	511	420	397	363	319
150	423	473	509	530	420	395	359	312
160	423	478	519	544	420	393	355	307
170	423	481	525	552	420	393	353	304
180	423	482	527	555	420	392	353	303

APPENDIX

Formula for calculating the daily direct radiation on a slope.

(1) The basic formula is:

$$I_d = I_o \int_{H_1}^{H_2} p^m \cos(\vec{X} \wedge \vec{S})\, dH$$

where

I_d = daily total of direct radiation in langleys.

I_o = the solar constant, generally taken at 2.00 ly. min^{-1}.

p = mean zenith path transmisivity of the atmosphere.

m = optical air mass.

H_1 and H_2 = the times when the sun shines for the first and last times on the slope each day.

$\vec{X}$ = a unit coordinate vector normal to the slope and pointing away from the ground.

$\vec{S}$ = a unit coordinate vector expressing the height and position of the sun.

$\wedge$ = a symbol for the angle between X and $\vec{S}$.

(2) The vectors $\vec{X}$ and S are expressed in easily measured terms such that

$$\begin{aligned}\cos(X \quad S) = & \left[(\sin\emptyset \cos H)(-\cos A \sin Z_x) - \sin H(\sin A \sin Z_x) \right.\\ & \left. + (\cos\emptyset \cos H) \cos Z_x\right] \cos\delta \\ & + \left[\cos\emptyset (\cos A \sin Z_x) + \sin\emptyset \cos Z_x\right] \sin\delta\end{aligned}$$

where

$\emptyset$ = the latitude of the slope.

δ = the declination of the sun.

H = the hour angle measured from solar noon, positively towards west.

A = the azimuth of the slope measured from the north through east.

Z_x = the zenith angle of $\vec{X}$.

(3) The optical air mass (m) can be expressed in terms similar to (2) above by means of the formula:

$$m = 1/(\cos\delta \cos\emptyset \cos H + \sin\delta \sin\emptyset)$$

This equation is valid only for the period when the sun is 20^{o} or more above the horizon. In the tropics, using the equation for daily totals results in an underestimation of less than 10% throughout the year. For low sun elevations the true value of m obtainable from tables should be used.

REFERENCES

Garnier, B. J., and A. Ohmura, 1968: " A Method of Calculating the Direct Short-Wave Radiation Incóme of a Slope", Journ. App. Meteor., October (in press).

Ohmura, A., 1968: "The Computation of Direct Insolation on a Slope", Climat. Bulln. (McGill Univ.), No. 3, pp. 42 - 53.

Tout, D. G., 1968: "Tables of Radiation in Barbados, 1964", Climat. Observations (New Series), McGill Univ., No. 2, July, 27 pp.

PRELIMINARY THOUGHTS ON LONG-WAVE RADIATIVE FLUX DIVERGENCE AND THE URBAN HEAT ISLAND

by

R. F. Fuggle*

The fact that a city or town often experiences higher temperatures then the surrounding country has been well established and a considerable literature on the subject has developed. The most detailed studies of city climate are probably those by Chandler (1962), for London, and Duckworth and Sandberg (1954) for San Francisco. Both these studies indicated the dependance of the urban heat island on city morphology, building density and on various meteorological parameters--notably windspeed and cloud cover. However, no systematic study has as yet been published in which the energy sources, or transformations, that sustain the rural-urban temperature differential have been the subject of investigation. Kratzer (1956) summarises estimates of heating due to combustion in several mid-latitude cities, while more recently, Summers (1964), and Daniels (1965), have calculated the component of city heating due to combustion, for Montreal and Edmonton, respectively. Little attention has, however, been focussed on changes between rural and urban locations that occur because of the different physical surfaces of the two environments.

If a thin surface layer in contact with the atmosphere is considered, the principle of conservation of energy requires that the net flux of energy through the surfaces of the layer must equal the

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change of energy within the layer per unit time. Assuming isotropic energy transfer, the energy balance for unit horizontal area may be expressed by,

$$Rn_{(0)} - G_{(-z1)} - E_{(0)} - H_{(0)} = \int_{-Z1}^{0} \rho C \frac{\delta T}{\delta t} dz \qquad \ldots(1)$$

where Rn is net radiation, G is heat flux due to conduction through the lower boundary ($-Z_1$), E is the energy flux due to evaporation, and H is the sensible heat transfer. The subscripts 0 and -Z1 refer to the atmosphere/surface interface and the lower boundary, respectively. ρ and C are the density and specific heat of the surface layer. All signs are positive for heat transfer into the layer. It is apparent that an urban-rural variation in any of the terms of (1) will lead to differences in the energy balance and probably to varying temperatures of the different surfaces.

Considering the terms comprising (1), ρc (= k, heat capacity) will be relatively large for the city's expanses of concrete and masonry, when compared to a vegetated surface, and heat storage will consequently be greater. The lack of transpiring surfaces in most urban areas will considerably reduce cooling by evaporation (E), and more energy will thus be available for partitioning between H and G. The Rn term is most easily considered by writing the radiative balance equation in the form

$$Rn = (Q + q)\ (1 = \alpha) + I\downarrow - I\uparrow \qquad \ldots(2)$$

Here the net radiative flux is expressed in terms of direct (Q) and diffuse (q) solar radiation incident on the upper surface of the layer; α the albedo of the surface; $I\downarrow$ the longwave thermal radiation from the atmosphere; and $I\uparrow$ the thermal radiation emitted from the upper boundary of the surface layer. The terms α and $I\downarrow$ will be directly influenced by surface characteristics and can therefore be expected to differ considerably between city and country. Kung et al (1964) have found the albedo of a city to be some 15% lower than that of rural areas, but no observations on the variation of $I\uparrow$ appear to have been published. The terms Q, q, and $I\downarrow$ are not related to the physical distinction between city and country surfaces, but rather to pollutants emitted by the city. Although the relative magnitudes of Q and q have not yet been published, (Q + q) is found by Hand (1943), and East (1968), to be lower for city locations. Although it is generally considered that $I\downarrow$ is greater over a city---because of the pollution haze---no actual comparative measurements of $I\downarrow$ in city and country appear to have been made.

The relation of the terms α and $I\uparrow$ to the physical nature of the surface, and the great variation of ρ and C among the different materials constituting the surface layer virtually prohibit the use of (1) for an integrated city or rural surface. An alternate approach must consequently be found if the processes involved in producing the urban heat island are to be understood on a quantitive basis.

By retaining the principle of conservation of energy and applying this to a discrete layer of air, rather than to a surface layer modifications are introduced that allow energy fluxes to be evaluated without reference to specific surface conditions. If unit area of a layer of air z to z_1 is considered, such that no net heat exchanges occur in the horizontal, the equation

$$Q_{(Z)} - Q_{(Z1)} = - \int_{Z}^{Z1} \frac{\delta Rn}{\delta z} dz + \int_{Z}^{Z1} \rho Cp \frac{\delta T}{\delta t} dz - \int_{Z}^{Z1} L \frac{\rho w}{\delta t} dz \quad \ldots (3)$$

expresses the heat balance due to: turbulent transfer of heat (Q) across the boundaries z and z_1; the divergence of net radiation in the layer, $\frac{\delta Rn}{\delta z}$, -- also referred to as flux divergence; temperature changes in the layer, $\frac{\delta T}{\delta t}$; and changes due to latent heat of condensation (L) of a mass of water (ρw) per unit volume. In the absence of condensation in the layer the last term of (3) may be ignored. By expressing the turbulent transfer of heat in terms of the thermal diffusion coefficient (K_h) and the temperature gradient between the top and bottom of the layer we obtain,

$$\frac{dT}{dt} = \frac{\delta}{\delta z} \left(K_h \frac{\delta \overline{T}}{\delta z}\right) + \frac{1}{C_p} \frac{\delta Rn}{\delta z} \quad \ldots (4)$$

Equation (4) indicates that air temperatures are determined by both turbulent and radiative processes. However, as $\frac{\delta T}{\delta z}$ is related to $\frac{\delta Rn}{\delta z}$ the two terms on the right of (4) cannot be treated independently. This problem has been examined at length by Godson (1965) and by Gaevskaya (1963), but remains one of the outstanding problems of heat exchange in the atmosphere. Although radiative flux divergence is usually ignored by micrometeorologists, Funk (1960) has shown that radiative flux divergence may be important, especially at night, even in unpolluted rural locations. It would therefore appear that an assumption of negligible flux divergence in a highly polluted urban atmosphere is not desirable, and that its contribution to the urban-rural temperature regime may be considerable. Indirect evidence to this effect is provided by numerous authors who have indicated that the urban heat island reaches its maximum extent under conditions favouring strong radiational exchanges. Equation (4) also draws attention to the possibility of K_h being variable. Möller (1950) has shown that the two components of $\frac{\delta}{\delta z}(K_h \frac{\delta T}{\delta z})$, namely $K_h \frac{\delta^2 T}{\delta z^2}$ and $\frac{\delta K_h}{\delta z} \cdot \frac{\delta T}{\delta z}$, may be several orders of magnitude larger than their sum. This implies a strong relation between temperature changes and small variations in the function $K_{h(z)}$. Should this variation of K_h be substantiated the different turbulence regimes of city and country will undoubtedly be a factor contributing to the thermal difference between them.

Indirect evidence to support the theory outlined above has been obtained from a preliminary study of the Montreal heat island*: a more thorough statistical evaluation of the evidence presented below is currently being undertaken.

The magnitude of the city-country temperature difference, taken to be positive if the city is warmer than the country, is found to be very variable through time. However, this phenomenon is masked if average values (monthly or daily) are compared; the city then showing temperatures consistently higher than the country. Taken on an hourly basis almost 30% of the observations indicate a lower temperature in the city than in the country. Further, 7% of the January and 11% of the

* In this study the hourly temperature differences between the McGill meteorological observatory in central Montreal and St. Hubert airport eight miles to the east of the city centre were taken to represent the city and rural locations. The initial study was undertaken for January and April 1968.

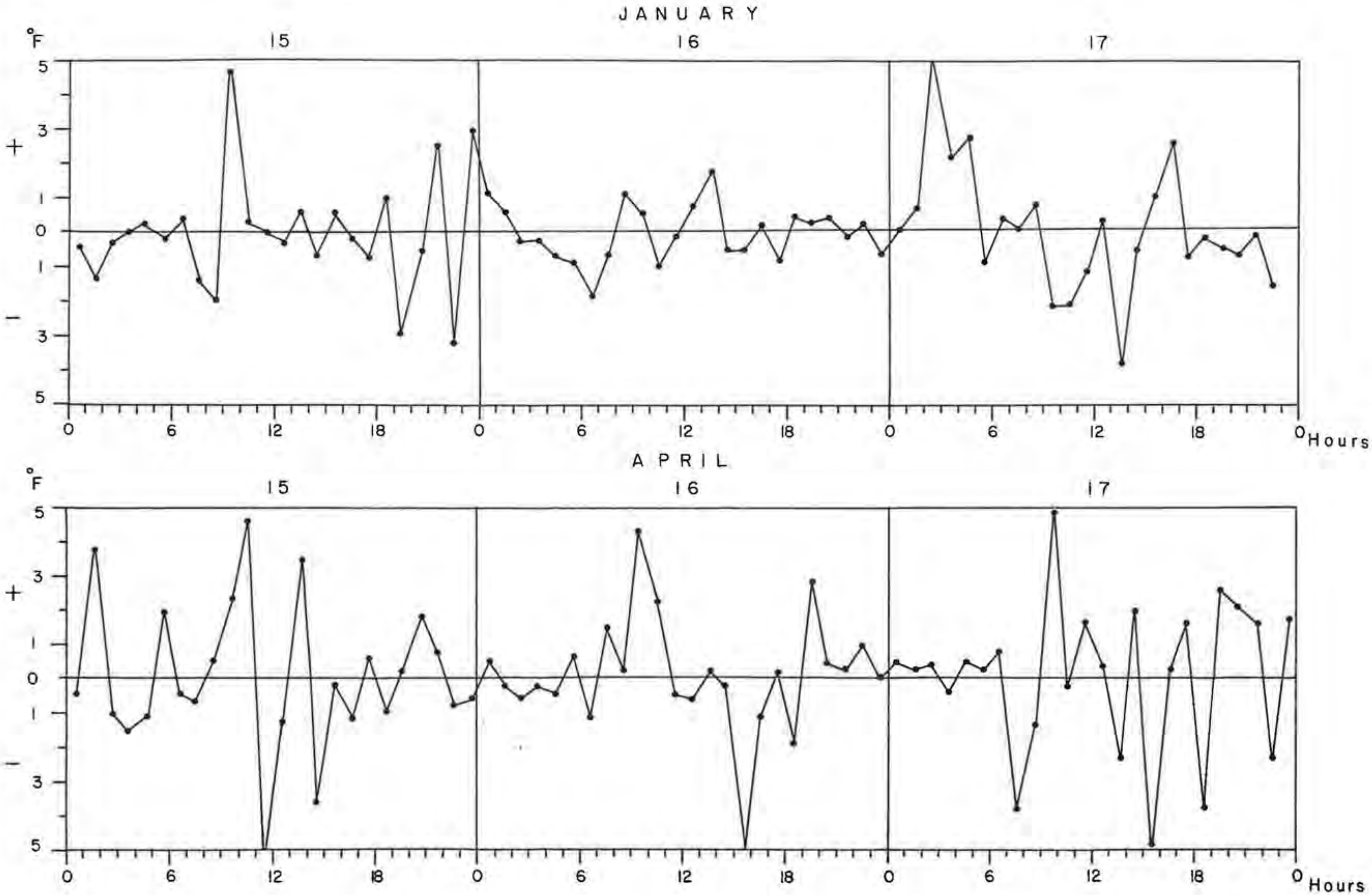

Fig. 1. Comparisons of Temperature between Montreal and St. Hubert Airport, January 15 - 17 and April 15 - 17, 1968.

April observations show changes in the rural-urban temperature difference of above 2.5°F per hour. Samples of the daily course of the changes in these two months are illustrated in Fig. 1, and the results for the whole of January and April are summarised in Table One.

TABLE ONE

NUMBER OF TEMPERATURE CHANGES EXCEEDING 2.5°F PER HOUR BETWEEN MONTREAL AND ST. HUBERT AIRPORT

		January				April				
Time of Day		00-06	06-12	12-18	18-24	00-06	06-12	12-18	18-24	Total
Total no. of changes		14	16	4	19	12	24	20	23	132
Direction of change	(Positive)	6	6	2	13	6	12	6	15	66
	(Negative)	8	10	2	6	6	12	14	8	66

It will be seen that positive and negative changes occur with similar frequency and that changes occur at all times of the day.* However, the fact that phases of city warming occur twice as frequently as periods of cooling between 1800 and 2400 hours E. S. T. is striking.

Explanation of these rapid and variable changes poses a problem. It is evident that heating due to combustion within the city is not sufficient explanation for these marked short-term fluctuations. Similarly, rapid changes in the physical surfaces of the two environments is highly unlikely. A feasible explanation may, however, be sought in terms of radiative flux divergence in the polluted air of the city.

* A change is considered to be positive if the city is warming with respect to the countryside, and negative if the city is cooling with respect to the countryside.

Funk (1960) has shown from his observations that temperature changes of over $10^{o}C$ per hour could be attributed to this cause. Brooks (1950), Elliott (1961), Gaevskaya (1962), Kondrat'yev (1965), and others have indicated from theoretical considerations that temperature changes of this magnitude may occur due to long-wave radiative flux divergence under suitable gradients of temperature and absorbing materials. The occurrence of a greater number of warming periods during the first half of the night appears to support this idea. The variation of $I\uparrow$ between city and country, together with the development of stable conditions favouring an accumulation of pollutants during this period, would both contribute to a strong convergence of long-wave radiation in the air layer immediately above the city.

In order to pursue this problem, research has been initiated in which long-wave radiative flux divergence, using the technique outlined by Funk in 1960, will be measured. Together with the radiation measurements, temperature gradients, as well as temperature variations, through time will be monitored. Finally, the finite difference form of equation (4) will be employed to assess whether or not heat is transfered differentially through a city's pollution haze and clear air, and whether radiative divergence contributes to the urban heat island.

REFERENCES

Chandler, T. J. (1962): "London's urban climate," Geog. Jour., 127, pp. 279-302.

Daniels, A. (1965): The urban heat island and air pollution with application to Edmonton, Alberta., M.Sc. Thesis, University of Alberta.

Duckworth, F. S., and J. S. Sandberg, (1954): "The effects of cities on horizontal and vertical temperature gradients," Bull. Am. Met. Soc., 35, p. 198.

East, Conrad C. (1968) "Total Solar Radiation recorded in Montreal and in the Countryside". Peper presented to 2nd Am. Congr. Can. Meteor. Soc., Calgary, June 3-5.

Elliott, W. F. and A. B. Lowe, (1961): "A numerical method for computing radiative temperature changes near the ground," GRD Research Note No. 69, AFCRL, Bedford, Mass.

Funk, J. P., (1960): "Measured radiative flux divergence near the ground at night," Q.J. Royal Met. Soc. 86, pp. 382-389.

Gaevskaya, G.N. et al, (1963): "Radiative heat flux divergence and heat regime in the lowest layer of the atmosphere," Arch. Met., Geoph. Biokl., 12 (1), pp. 95-108.

Godson, W. L. (1965): "The role of radiative flux divergence in the surface boundary layer," First Canadian Conference on Micrometeorology, Pt. 1, pp. 145-162.

Hand, I.F. (1943): "Transmission of total and infrared radiation through a smoky atmosphere," Bull. Am. Met. Soc., 24, pp. 201-204.

Kondrat'yev, K.Y (1965), Radiative heat exchange in the atmosphere, Pergamon Press, New York and London.

Kratzer, P. A. (1956) The climate of cities, Translation from German by American Meteorological Society.

Kung, E.C. et al (1964) "Study of a continental surface albedo on the basis of flight measurements." Monthly Weather Review, 92, pp. 543-64.

Summers, P. (1964): "An urban ventilation model applied to Montreal", unpubl. Ph.D. Thesis, McGill University, Montreal.

EVAPORATION MEASUREMENTS FOR LAC HERTEL MONT ST. HILAIRE

by

D. S. M. Munro*

During the late summer and early fall of 1967 a study of evaporation from a small lake at Mont St. Hilaire was carried out at the suggestion of Colonel P. D. Baird, the Director of the Gault Estate. The main objective of the 1967 study was to estimate lake evaporation by three methods: a class "A" evaporation pan; a United States Weather Bureau nomograph; and a slightly modified form of Penman's formula (Penman 1943). A secondary aim was the assesment of the role of evaporation in the heat and water balance of the lake.

Procedure: Observations were taken daily at 08.00 E. S. T. during a twelve week period, July 3 until September 24, from a climatic station on the surface of Lac Hertel. Within this period, a four-week series of specialised observations on the water balance of the lake lasted from August 21 until September 17. Two Stevenson screens and a class "A" evaporation pan were mounted over the water on stands near the southern shore of the lake. Conventional instruments obtained from the Meteorological Branch of the Department of Transport, Canada,

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were used to measure air temperature, water temperature, vapour pressure, the dew point, wind speed and rainfall. This information formed the basis for empirical estimates of evaporation and net radiation. Global radiation values were obtained from the Mont. St. Hilaire climatic station. Stream gauging facilities and lake level measurements provided the additional information required for an approximate assessment of the water budget of Lac Hertel.

Class "A" pan evaporation estimates are seldom truly representative of lake evaporation (Sellers 1965) and it is customary to multiply them by a pan coefficient of 0.70 in order to obtain more correct values. Kohler, Nordenson and Fox (1958) state that this value applies only on an annual basis and consequently a different value had to be chosen for this study. There is much experimental evidence to suggest that these coefficients change from values less than unity in the summer, to more than unity in the fall (Sellers 1965). A study on the Weyburn Reservoir (McKay and Stickling 1961) yielded a coefficient of 1.06 for a period lasting from late July until late October. Consequently it was decided that a pan coefficient of 1.00 would be acceptable for this study.

The United States Weather Bureau nomograph was developed by Kohler (1954) for estimating class "A" pan evaporation. The metric version shown in Fig. 1 has been adapted from a diagram appearing in an article by Roberts and Stall (1966). At the suggestion of the authors (written communication) mean daily water temperature was substituted for air temperature.

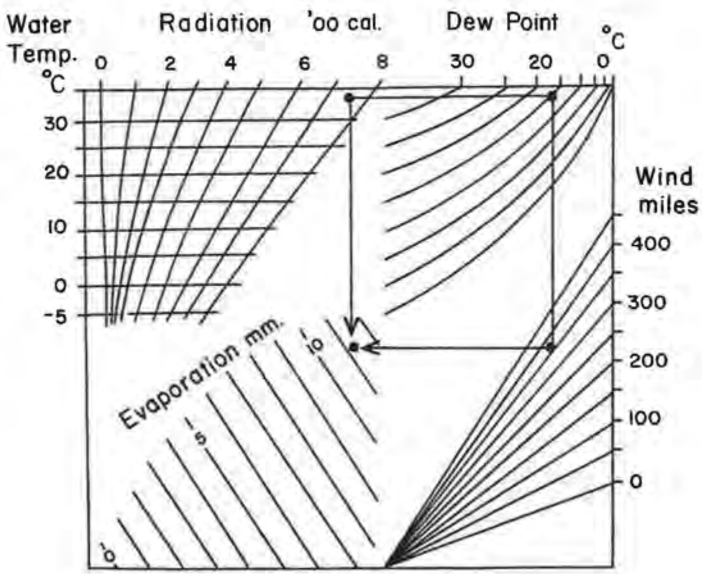

Fig. 1. Nomograph for estimating Class "A" Pan Evaporation (adapted from Roberts & Stall)

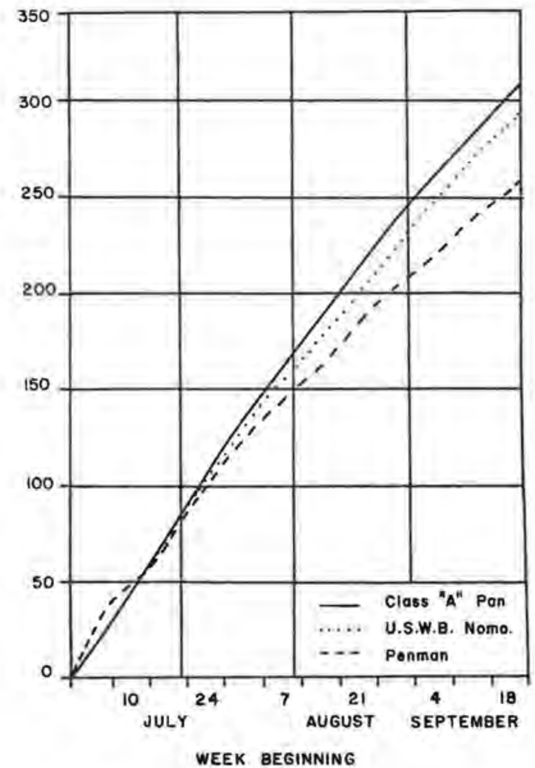

Fig. 2. Cumulative values of evaporation at Lac Hertel (in mm.)

Penman's formula was used essentially in its original form (Penman 1948) except that the wind function used by Penman was replaced with a formula appearing in a paper by Wang and Wang (1962). The substitution was made because, although the new formula did not differ structurally from the previous one its constants had been determined under climatic conditions comparable to those experienced at Mont. St. Hilaire.

Results: Mean daily values of evaporation for the Lac Hertel and Mont. St. Hilaire stations are given in Table One. The highest estimates occurred during the week of July 10 when the highest net radiation inputs were calculated. All of the methods used showed a fairly close correspondence between weekly changes in evaporation and net radiation. This was especially true of evaporation estimates obtained from Penman's formula. Cumulative evaporation values for the lake are graphed in Fig. 2. The class "A" pan and the nomograph yielded the highest totals, the latter being slightly the lower of the two. Such similarity between the two methods has been observed before (Roberts and Stall 1966) and it is further illustrated by the regression line in Fig. 3 which shows almost a one-to-one correspondence between the two methods and a high correlation coefficient of 0.93. The total of 250 mm. yielded by the Penman formula was approximately 50 mm. lower than those of the other two methods. It can be seen from Table Two that evaporation was an important water loss factor for Lac Hertel. It was second only to the intake of water by the town of Beloeil. Rainfall was the

TABLE ONE

MEAN DAILY VALUES OF EVAPORATION

(mm. day^{-1})

Week Beginning	Lac Hertel			Mont St. Hilaire
	Class "A" Pan	Nomograph	Penman	Class "A" Pan
July 3	3.7	3.7	4.1	3.8
10	5.0	4.6	4.1	4.9
17	4.4	4.2	4.0	4.1
24	4.2	3.7	3.6	4.2
31	3.9	4.1	3.3	3.6
Aug. 7	3.3	2.9	2.5	2.9
14	3.6	3.2	2.8	2.8
21	3.5	3.4	3.3	3.3
28	3.7	3.3	2.1	3.8
Sept. 4	3.3	3.4	2.7	3.8
11	3.1	3.2	2.7	3.1
18	2.2	2.3	1.1	2.3

TABLE TWO

THE WATER BALANCE OF LAC HERTEL

(1000 l. wk.$^{-1}$)

Components	Week Beginning				Totals
	Aug. 21	Aug. 28	Sept. 4	Sept. 11	(1000 l.)
Receipts					
Rainfall	1,660	13,380	2,380	nil	17,420
West Creek	2,259	2,285	1,630	1,302	7,476
North Creek	448	729	380	266	1,823
	+ 4,367	+16,394	+ 4,390	+ 1,568	+ 26,719
Expenditures					
Beloeil Intake	22,837	22,554	22,260	22,470	90,121
Evaporation	8,930	9,350	8,380	7,760	34,420
Groundwater	6,545	7,660	7,188	5,034	26,427
Outflow	2,705	2,480	2,352	2,094	9,631
	-41,017	-42,044	-40,180	-37,358	-160,599
Change in Storage					
Lake Level	-36,650	-25,650	-35,790	-35,790	-133,880

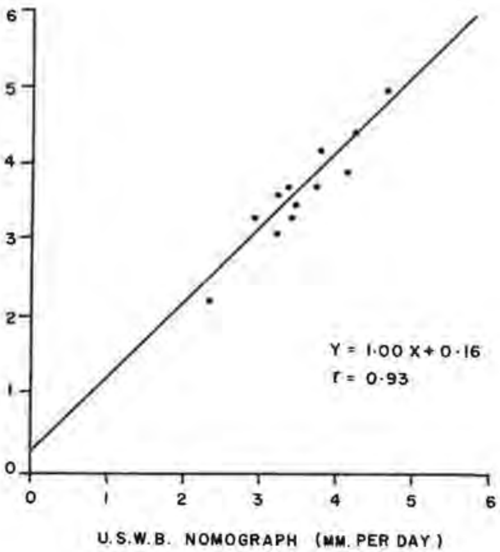

Fig. 3. Correlation between Penman formula and nomograph estimates of evaporation

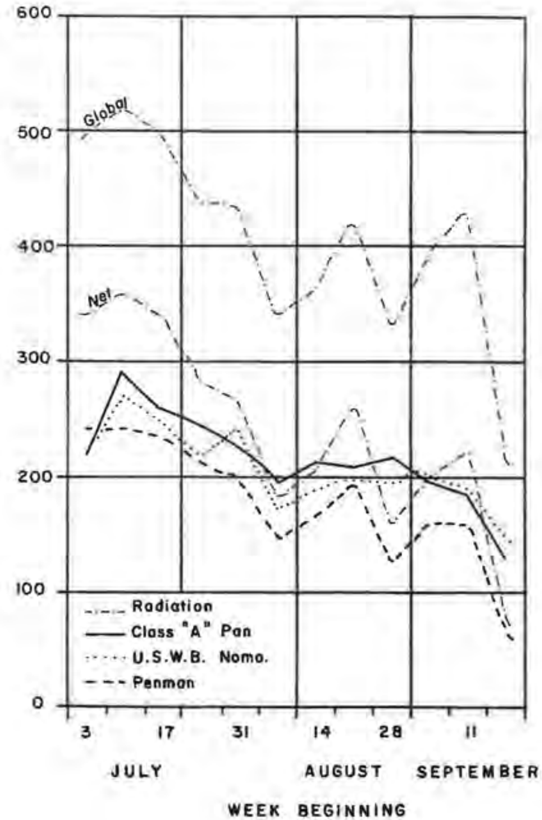

Fig. 4. Evaporation rates and radiation values, Lac Hertel

major contributor of water to the lake. Streamflow had only a minor effect on the water budget. The loss of water through the ground appears to be very high. This is probably because ground-water was not actually measured but remained a residual in the water balance equation. Consequently, it contains any errors made in measuring the other components. It was expected that evaporation would be the major utiliser of energy (Sellers 1965) and Fig. 4 illustrates that this was so. This diagram shows anomalous weeks when evaporation estimates for the pan and nomograph exceeded net radiation values. The Penman estimates were never excessive in this regard.

Conclusions: There was no absolute standard against which to judge the performance of the methods used. If the possibility of advected energy is dismissed, Penman's formula gives the best performance since evaporation estimates obtained in this manner never exceded net radiation values. The close correspondence between the class "A" pan and the nomograph leaves little to chose between these two methods on the basis of performance. The nomograph is preferable from the viewpoint of convenience since it is difficult to maintain a class "A" pan over a water surface and the danger of "splash" error is always present. However since the nomograph is an estimator of pan evaporation its values would presumably have to be corrected by coefficients as well in order to obtain representative values of evaporation.

If one were willing to accept that the pan coefficient was consistently equal to 1.00 the discrepancies between energy used in evaporation and that supplied by net radiation could be explained in terms of extra energy advected into the site. Such a conclusion would serve as a warning to use with caution such techniques as the Bowen ratio, the wind profile method, and others which assume the absence of the advective influences (Sellers 1965).

Although the methods used to measure evaporation were only approximate they served sufficiently to illustrate its importance in the heat and water balance of the lake. On the basis of these measurements it appears that the total evaporation from Lac Hertel during the period studied was in the vicinity of 250 to 300 mm.

Acknowledgements

Meteorological instruments for the study were provided by the Department of Transport, Canada, and measurements of water drawn from the lake were obtained from the municipality of Beloeil. I would like to thank Professor B. J. Garnier for supervising the study and Dr. T. R. Oke for proof-reading the manuscript.

ERRATA

It is regretted that the references for the article by D.S.M. Munro, "Evaporation Measurements for Lac Hertel, Mont St. Hilaire" (Climat. Bulln. No.4, July 1968, pp.40-48) were inadvertently omitted. These references are:

Kohler, M.A., Nordenson, T.G., and Fore, W.E., 1958: Pan and lake evaporation, pp. 38-60. In Water Loss Investigations: Lake Mead Studies. U.S. Geological Survey, Professional paper 298, Washington.

McKay, G.A., and Stickling, W., 1961: Evaporation computations for prairie reservoirs. Proc. Hydrol. Symp. No.2, Evaporation. Queen's Printer, Ottawa, 135-163.

Penman, H.L., 1948: Natural evaporation from open water, bare soil, and grass. Proc. Roy. Soc. London, A 193, pp. 205-208.

Sellers, W.D., 1965: Physical Climatology. University of Toronto Press, Toronto, pp. 272.

Wang, J.Y., and Wong, S.C. 1962: A simple graphical approach to Penman's method for evaporation estimates. Journ. Appl. Meteor. 1, pp. 582-588.

A NOTE TO COMPARE THE RECORDS FROM THREE RAIN GAUGES SIMILARLY EXPOSED AT MONT. ST. HILAIRE, QUEBEC.

Between June 12, 1967 and June 12, 1968 rainfall was measured in three raingauges similarly exposed at the McGill Mont St. Hilaire climatological research station. Exposure of the gauges was such as to meet the requirements of the Canadian Meteorological Branch for the standard Canadian three inch raingauge, as well as the requirements of the British Meteorological Office for the M. O. Mark II gauge, which is five inches in diameter. In addition a "True-chek" plastic gauge with a 5.82 square inch rectangular receiver, manufactured by the Edwards Manufacturing Company, was placed to the south of the three-inch and five-inch gauges. The three gauges were placed so as to form an equilateral triangle with six foot sides. During the experimental period the raingauges were read twice daily, at 0800 and 1800 Eastern Standard Time, using tapered rain measures for the standard three and five-inch gauges, and reading the True-chek gauge from the calibration markings on its tapered stem. All measurements were made to the nearest 0.01 inches, all observations of less than 0.005 inches were recorded as "trace". No attempt has been made to compare snowfall received by the gauges.

A total of one hundred and nine comparative observations were obtained, yielding the following results:

(1)

	Annual Total	Mean Value for a Single Observation
3" Gauge	23.89"	0.2192"
5" Gauge	24.08"	0.2209"
True-chek	24.18"	0.2218"

(2) Summary Table for Analysis of Variance

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Total	326	29.7596		
Between Gauges	2	0.0004	0.0002	0.00213
Within Gauges	324	29.7592	0.0939	

(3) Distribution of Differences between Gauges

Gauges	Differences -0.03	-0.02	-0.01	0	0.01	0.02	0.03	0.06	0.07
3"-5"	3	1	17	79	9				
3"-TC	3	4	27	66	7	1		1	
5"-TC	2	3	23	68	8	2	2		1

(4) Relation of Differences and Rainfall Amount

(a) Three and Five inch gauges

Total Rainfall*	Differences** -0.03	-0.02	-0.01	0	0.01	0.02	0.03
0 - 0.25	1		9	63	7		
0.26 - 0.50	1		3	13			
0.51 - 0.75			3	1			
0.76 - 1.00				1	2		
+1.00	1		2	1			

* As recorded by three inch gauge.

** Three inch record less five inch record.

(b) Three inch and True-chek gauges.

Total Rainfall*	Differences** -0.03	-0.02	-0.01	0	0.01	0.02	0.03	0.06
0 - 0.25	2	2	20	51	6			
0.26 - 0.50	1	1	5	9				
0.51 - 0.75		1	1	3	1			
0.76 - 1.00			1	3				
+1.00						1		1

* As recorded by three inch gauge.

** Three inch record less True-chek record.

(c) Five inch and True-chek gauges.

Total Rainfall*	Differences** -0.03	-0.02	-0.01	0	0.01	0.02	0.03	0.07
0 - 0.25	2	2	15	53	7		1	
0.26 - 0.50		1	5	11				
0.51 - 0.75			1	2		1		
0.76 - 1.00			2	1	1			
+1.00				1		1	1	1

* As recorded by the five inch gauge.

** Five inch record less True-chek record.

From the analysis of variance summary table it is apparent that no statistically meaningful differences exist between the means of the three raingauges. This is also evident from the differences between the annual totals, amounting to only 0.1% of the total. The tables showing the differences as related to the amount of rainfall indicate that with low rainfall the True-chek gauge appears to have a tendency to higher values than recorded by the three and five inch gauges. Similarly the five inch gauge read higher than the three inch gauge more often than it under read. Nevertheless, over sixty percent of the observations taken with low rainfall totals show no difference between the gauges. With higher totals the True-chek gauge seems to give lower values than measured on the standard gauges. This does not, however, appear to be the case between the three and five inch gauges.

In conclusion it may be stated that the inconsistency of the differences between the gauges prohibits the formulation of statistically valid relations between the gauges. The observed differences are thus most likely to have arisen from measurement errors and as the differences are of the same order as the maximum errors inherrent in the instruments no statement as to the superiority of any particular gauge can be made.

R. F. Fuggle.

RESEARCH REPORT

Two of the articles in this number of CLIMATOLOGICAL BULLETIN, that by R.F. Fuggle and Atsumu Ohmura (pp. 1 - 20) and by B.K. Basnayake (pp. 21 - 30), indicate some of the progress which has been made during the past six months in energy budget studies. There has been, however, a considerable amount of other activity in this field the results of which are not yet ready for presentation. In Barbados a series of 50-hour continuous observation experiments in three different locations has been undertaken. These have concentrated on temperature and humidity recording at two levels by means of wet and dry bulb thermistors and Assmann psychrometers, together with net radiation, and soil heat flux measurements. The work has been closely associated with the Barbados experiment of Florida State University (Garstang, 1968) and has, indeed, been planned in co-operation with the Florida group.

The greater part of the energy budget work at Mont St. Hilaire is outlined and reported on in the article by Fuggle and Ohmura in this BULLETIN (pp. 1 - 20). The large amount of data collected, however, has yet to be more fully analysed. Additional work is currently being undertaken to measure the variations in direct and sky-diffuse solar radiation on slopes of different angles and azimuths. This is an essential test for the validity of the radiation mapping techniques recently developed (Ohmura, 1968).

In the weeks prior to the experiment at Mont St. Hilaire a thorough survey and re-organization of the experimental side was undertaken under the direction of R.F. Fuggle. The changes were undertaken in order, (a) to accommodate additional instruments, (b) to provide better exposure for the existing radiation instruments, (c) to provide greater protection for the electronic systems during electric storms, and (d) to design a system which would allow for future installation of electronic instruments without major changes having to be effected in the existing system.

The final instrument arrangement (Fig. 1) was determined very largely by factor (b) above. The net-radiometer as well as the up-and down- facing pyranometers were positioned to provide the clearest possible horizon, together with the greatest expanse of unobstructed grass surface beneath the instruments. The shaded pyranometer, actinograph, yellot solar energy integrator, and sunshine recorder were then positioned with regard to an unobstructed skyline and in positions such that their shadows would not influence surface albedo or net radiation measurements. The remaining instruments were positioned (a) so as not to affect the radiation measurements -- achieved by placing sub-surface sensors or

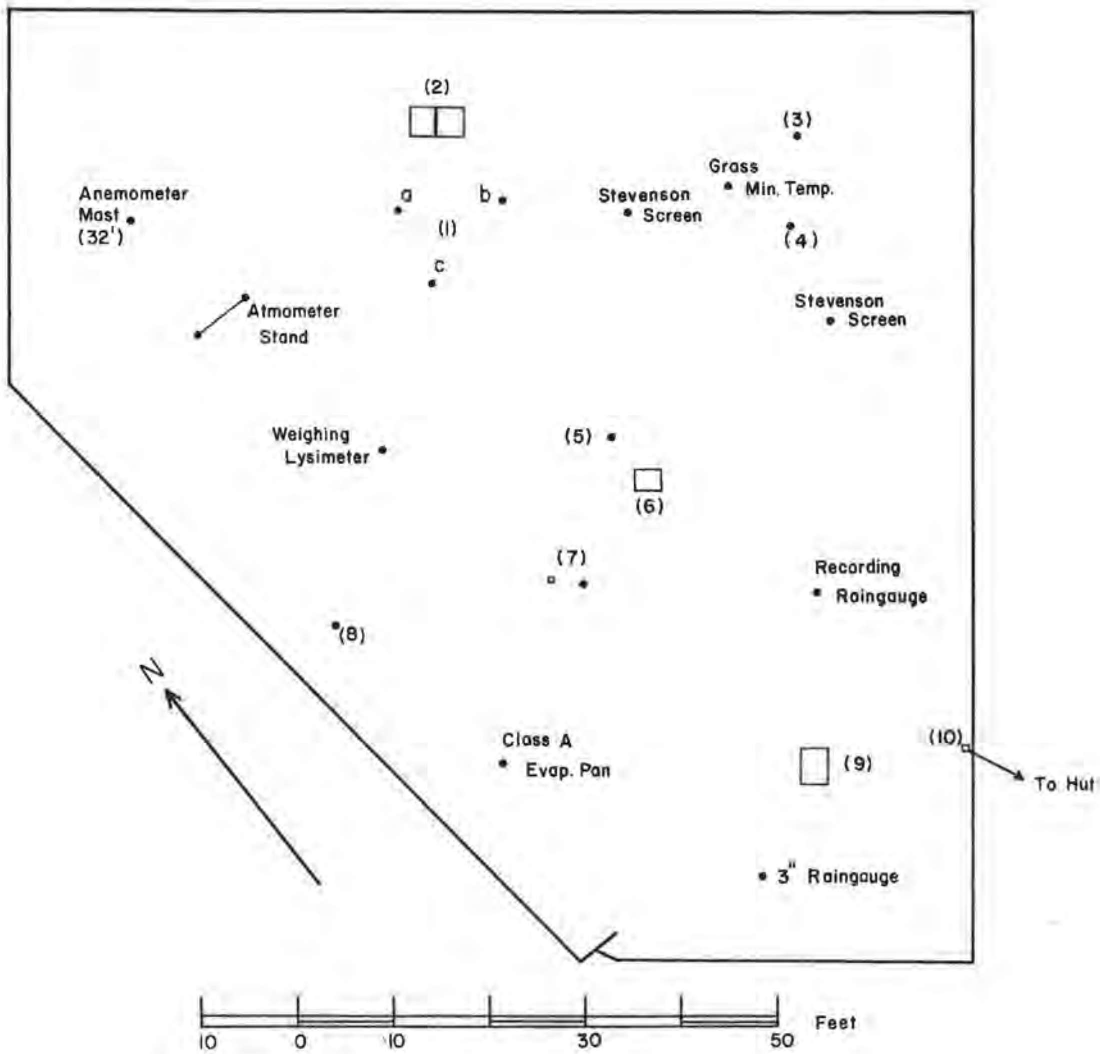

Fig. 1. The Experimental Site at Mont St. Hilaire
Key to numbers: 1 Profile masts; (a) wind, (b) Assmann, (c) thermistors. 2 Boxes for portable recording systems. 3 Thermohygrograph in screen at 0.2 m. 4 Max. & Min. Thermometers at 1 ft. 5 Sunshine recorder and bimetallic actinograph and silicon cell radiation recorder. 6 Surface temperatures. 7 Net radiometer and Kipp pyranometers. 8 Shaded Kipp pyranometer. 9 Soil temperatures & Soil heat flux. 10 Junction box and cables to hut.

physically small instruments closest to the radiation sensors -- (b) to provide maximum unobstructed north-south fetch across short grass for the wind, temperature, and humidity profile sensors, and (c) to be at least thirty feet from any of the apple trees in the orchard in which the station is situated.

Protection for the electronic systems and better facilities for the existing and future installations were achieved by providing a 1 1/2" polythene conduit, buried one foot below the surface , between the instrument enclosure and the recording hut. Fourteen pairs of individually shielded twisted electronic cable pass through the conduit, as well as a 1/8" polythene tube providing aspiration for the net radiometer. Direct electrical connections between the recording hut and two easily accessible water-tight junction boxes within the instrument enclosure are now possible. In addition a four foot copper earthing rod was sunk in the enclosure and the housings of all electronic sensors led directly to earth via copper wire. All recorders are separately earthed at the recording hut. Although not completely removing effects due to electric storms no instruments have been rendered inoperative by storms since this system was installed.

Within Montreal, the urban heat island studies reported in CLIMATOLOGICAL BULLETIN No. 3((p. 36 - 41) have been continued. The survey has now been extended to encompass the total urbanized area of the island of Montreal. In October another intensive series of observations will be conducted in co-operation with Dr. East of the University of Montreal. If it is found possible to acquire automatic temperature recorders special attention will be focussed on spatial and temporal variations of the "cliff-like" margins of the heat island. The programme is preparing to undertake radiation studies in the city (see pp.31 -39 of this Bulletin). The investigation is designed to measure the contribution made by infra-red radiation flux divergence, to the urban heat excess. The choice of sensors has been made in consultation with the National Radiation Laboratory, Scarborough. Attention is now being turned to the design and construction of a precision-made mast to enable the net radiometers to be freely moved in the vertical. The site for these experiments has yet to be finalised.

During the spring two Thornthwaite 6-level wind profile systems were purchased. These formed part of the equipment used in a joint McMaster-McGill research project at,the Horticultural Experiment Station, Simcoe, Ontario. Four 6-level temperature and wind profile masts were set up in a wheat field to study the adjustment of profiles and eddy fluxes following a change in the surface properties. Approximately 120 sets of data were gathered (each period averaged over 10 min.), and are now being reduced and analyzed. This work is being undertaken by Dr. T. R. Oke (see CLIMATOLOGICAL BULLETIN No. 3, p. 55).

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References

Garstang, Michael and N. E. LaSeur, 1968: "The 1968 Barbados Experiment", Bulln. Amer. Meteor. Soc., Vol. 49, No. 6, June, pp. 627-635.

Ohmura, Atsumu, 1968: "The Computation of Direct Insolation on a Slope," Climat. Bulln. No. 3, January, pp. 42-53.

NEWS AND COMMENTS

Tim R. Oke has been appointed a member of the McGill Interdisciplinary Committee on Air Pollution (MIDCAP). The Committee has been established to enable better communication between those persons both on and off campus who are interested in the subject.

In February, Messrs. Morley Thomas and Gordon Mackay, of the Department of Transport (Meteorology Branch) visited the Geography Department. They met students and staff, and discussed with them the work of the Meteorology Branch and career opportunities in climatology.

B. J. Garnier and Atsumu Ohmura attended the Second Annual Congress of the Canadian Meteorological Society at Calgary in June, where they presented a paper on "Topographical Variations in Direct Short-Wave Radiation Income at Mont St. Hilaire, Quebec."

Tim R. Oke , accompanied by R. F. Fuggle and Scott Munro, attended the eighth conference on Agrometeorology organised by the American Meteorological Society in Ottawa at the end of May. During the summer Dr. Oke also attended meetings at Minneappolis (Air Pollution Control Annual Meeting), at Logan, Utah (American Association for the Advancement of Science) and at Guelph, Ontario (conference on Eddy Correlation Techniques.)

McGill University
Department of Geography

C L I M A T O L O G I C A L   R E S E A R C H   S E R I E S

No. 1. Two Studies in Barbadian Climatology
by Wayne R. Rouse and David Watts.
65 pp., July 1966, price: $6.00.

No. 2. Weather Conditions in Nigeria
by B. J. Garnier.
163 pp., March 1967, price: $7.50.

No. 3. The Climate of the Rupununi Savannas - A Study in Ecological Climatology
by David B. Frost.
92 pp., December 1967, price: $6.50.

No. 4. Temperature Variability and Synoptic Cold Fronts in the Winter Climate of Mexico
by John B. Hill.
(In preparation).

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