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HEAT AND MOISTURE TRANSFER ABOUT PAN EVAPORIMETERS

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Abstract: Routine measurements with pan evaporimeters at Griffith, N. S. W., have been related to radiation-intensity values estimated from formulae, and to the usual meteorological records of air temperature and vapour pressure. These data are too crude for accurate estimation of the resistances to the flows of heat and water vapour from an evaporimeter. However, use of the data illustrates a procedure for deriving values for the resistances. The approximate values obtained do not indicate that buoyancy appreciably promotes heat transfer from the water surface.

1. INTRODUCTION

Buoyancy promotes the convection of heat from an exposed surface, and thus increases the eddy diffusivity. In consequence, the eddy diffusivity of heat may well exceed that of moisture (Swinbank, 1955). However, any differences between heat and moisture diffusivities are reduced near the ground (Slatyer and McIlroy, 1961), and it has been assumed that they are effectively the same in the case of evaporation from a water surface (Bowen, 1926; Cummings and Richards, 1927; Ferguson, 1952). This assumption is briefly considered in the present paper, in the light of routine pan-evaporation data collected at a conventional meteorological station in a semi-arid area. The station is at Griffith, N. S. W., in the grounds of the C. S. I. R. O. Irrigation Research Laboratory, where a U. S. Weather Bureau Class A pan evaporimeter has been installed for over three years, and an Australian Standard Tank for a longer period. It will be shown that the available data are inadequate for firm conclusions, but the method of analysing the data is illustrated and provides some indication of the relationship between the diffusivities.

2. THE WATER VAPOUR DIFFUSION RESISTANCE

The resistance to water vapour diffusion may be derived from four equations. The first is the energy balance -

$$R = LE + H + S \qquad \ldots (i)$$

where R is the net incident-radiation intensity,

L is the latent heat of evaporation,

E is the water-loss rate,

H is the sensible-heat flux from water to atmosphere

and S is the rate of heat storage.

The last term is commonly ignored when changes over long periods are considered. The other terms of the right-hand side of equation (i) may be expressed by Dalton-type equations -

$$LE = (e_s - e_a) / r_w \qquad \ldots (ii)$$

$$H = (T_s - T_a) / r_h \qquad \ldots (iii)$$

where e_s and e_a are respectively the vapour pressures of the water surface and the atmosphere at screen height,

T_s and T_a are the temperatures of the water surface and the atmosphere at screen height (^oC),

and r_w and r_h are the diffusion resistances.

The factors (e_s) and (T_s) may be roughly related by an empirical expression which is accurate within 1 mm Hg over the range 10 - 35°C, as follows -

$$e_s = 4.8 \exp \frac{T_s}{16.1} \text{ mm Hg} \qquad \ldots \text{(iv)}$$

From equations (ii) and (iv), it follows -

$$T_s = 37 \log_{10} (r_w . LE + e_a) - 25.3 \qquad \ldots \text{(v)}$$

In some circumstances the water-surface temperature (T_s) and the air temperature (T_a) will be equal, and then the radiation and evaporation terms will be equal also, assuming that the storage of heat is negligible. Also, the term e_s in equation (ii) becomes the value e_{sat}, which is the saturation vapour pressure at the mean ambient temperature (T_a). In other words, the following equation obtains -

$$r_w = \frac{e_{sat} - e'_a}{LE'} \qquad \ldots \text{(vi)}$$

where the apostrophe indicates conditions when R and LE are similar, e.g. within 0.01 cal/cm^2. min, say. Equation (vi) allows calculation of the resistance (r_w).

Insertion of the derived value (r_w) into equation (v) gives the effective water-surface temperature (T_s) in any set of circumstances, assuming that changes of radiation, temperature and vapour pressure leave the resistance unaffected. The resistance varies with the wind-speed (Kohler et al. 1955), but here only the average value of the resistance (r_w) is considered, relating to average wind conditions and estimated from monthly-mean data. At Griffith the daily wind-run at 50 cm height is about 60 miles, and for 41 monthly means the standard deviation was found to be 12.6 miles. This is about 20 per cent of the average, and such a variation alters the factor given by Kohler et al. (loc.cit.), which is equivalent to the resistance (r_w), by only 7 per cent.

The effective constancy of the resistance can be checked in the case of a Class A pan evaporimeter by comparing measured values for the surface temperature (T_s) with those calculated from equation (v), using a value of resistance (r_w) obtained from equation (vi). In making this check, it is necessary to use the customary approximations in deriving mean values. The daily mean temperatures (T_s and T_a) are taken as the averages of the daily maximum and minimum temperatures, and the monthly mean is the average of the daily means. The daily mean vapour-pressure is, as usual, taken as that measured at 9a.m.

As regards estimating the radiation intensity (R) from the Griffith records, recourse has to be made to empirical formulae as follows -

$$R = (1 - s) R_s - R_L \qquad \ldots \text{(vii)}$$

$$R_s = R_a (0.23 + 0.54 \frac{n}{N}) \qquad \ldots \text{(viii)}$$

$$R_L = (0.18 - 0.09 \sigma T_k^4) (0.20 + 0.8 \frac{n}{N}) \qquad \ldots \text{(ix)}$$

where s is the surface reflectivity of water (taken as 0.05),

R_s is the mean incoming shortwave-radiation intensity,

R_L is the mean net outgoing longwave-radiation intensity,

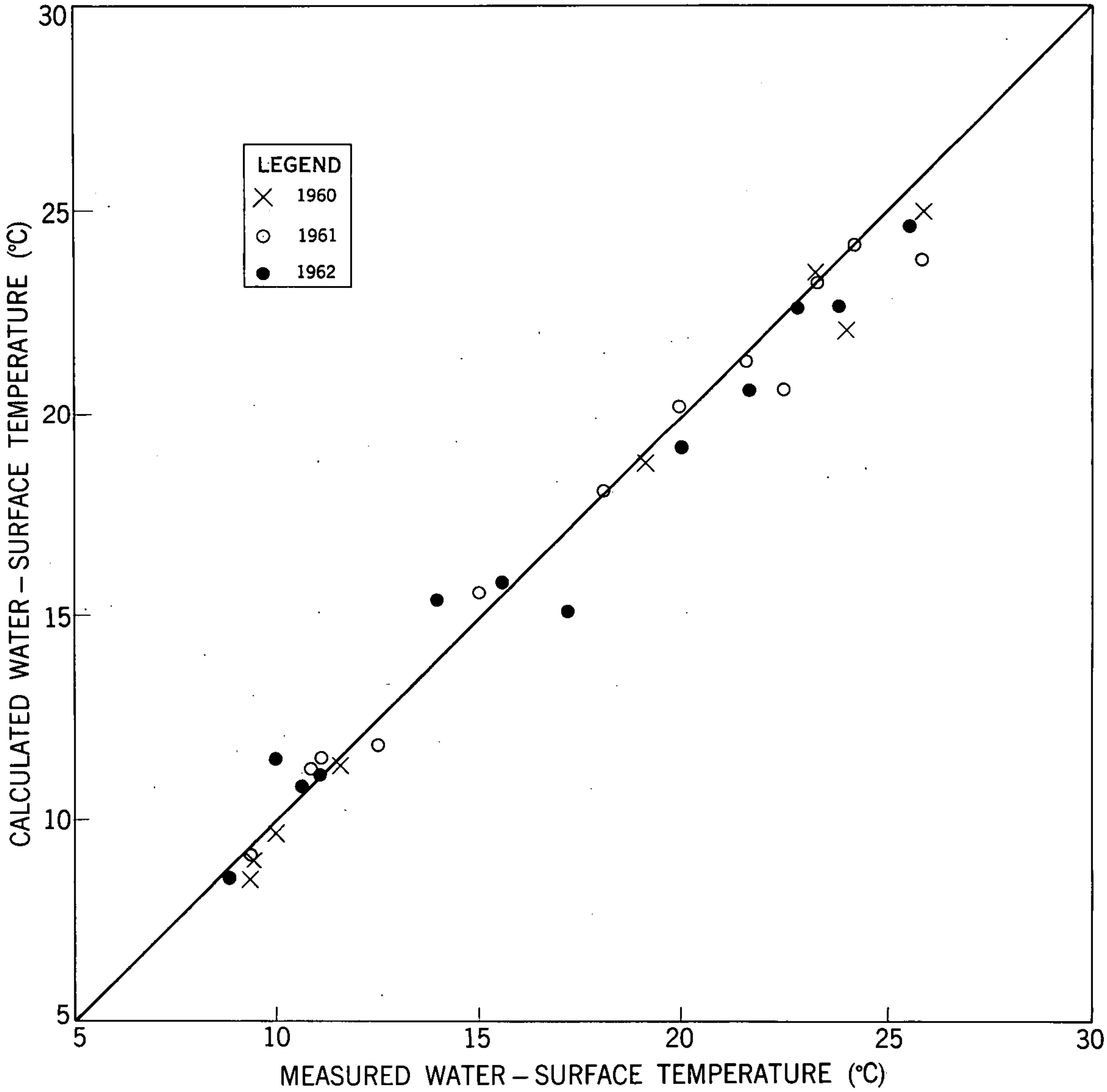

Fig. 1 Correlation of values of the monthly – mean water – surface temperature derived from measured maximum and minimum temperatures, and values estimated from equation (v). The line is that of equality.

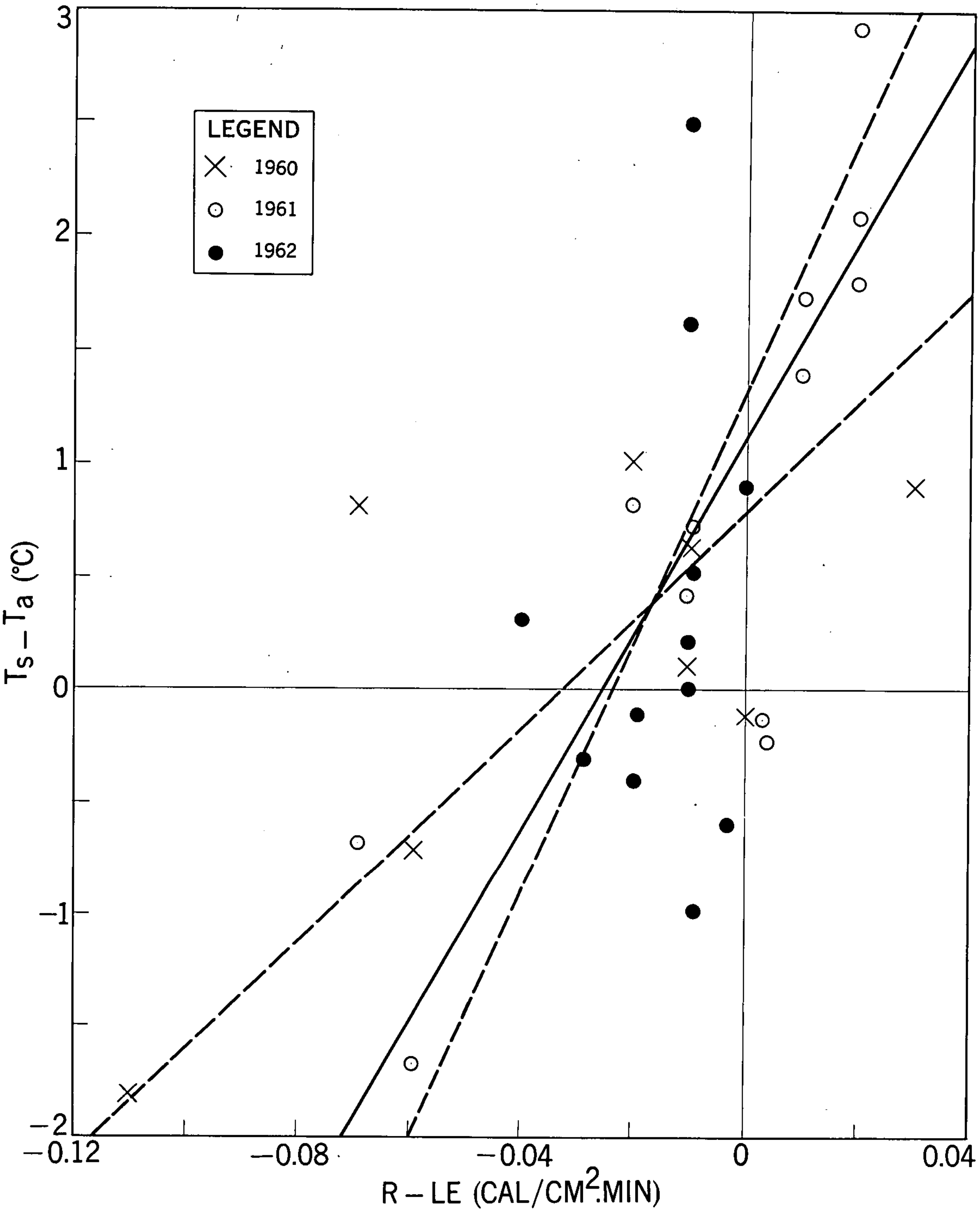

Fig. 2 Correlation of estimated monthly — mean values of the nominal sensible — heat flux (R − LE) from the water in a United States Weather Bureau Class A pan evaporimeter, and the difference between the temperatures of the water surface (T_s) and the air (T_a). The outer lines are regression lines and the inner line expresses the derived functional relationship.

R_a is the theoretical monthly-mean radiation intensity for the appropriate month and latitude, assuming no atmospheric obscuration (Brunt, 1939),

n is the mean daily number of hours of bright sunshine,

N is the maximum possible hours of sunshine,

σ is a constant (8.2×10^{-11} cal/cm^2.min.$^{\circ}K^4$),

and T_k is the mean air temperature (T_a + 273).

Equation (viii) results from averaging the constants in three available equations - (a) one based on the dependence on latitude shown by Scholte-Ubing (1959), (b) the empirical expression found by de Vries (1958) for Deniliquin, 110 miles from Griffith and about 1° further south, and (c) the expression used by Penman (1948). Equation (ix) gives the net outgoing longwave radiation, which is the difference between the gross outgoing radiation (i.e. σT_k^4, assuming an emissivity of unity) and the incoming longwave radiation. The latter is given by an expression due to Swinbank, for clear-sky longwave radiation, if one assumes a negligible cloud effect in a semi-arid area. A slightly different form of the expression used here has been published recently (Swinbank, 1963). Any small errors due to the difference, or to the two assumptions just mentioned, are unimportant, since the term R_L in equation (vii) is only a minor component of the net radiation intensity (R).

These equations were used to obtain the figures for radiation (R) in Table 1, and then values of the impedance (r_w) were derived from equation (vi) for the cases when the terms R and LE differed by 0.01 cal/cm^2.min or less. The water-surface temperature (T_s) was calculated from the median value of the resistance, i.e. 26 mm Hg.cm^2.min/cal, in conjunction with equation (v). As a result, it may be seen in Table 1 that the average difference between the measured and calculated water-surface temperatures is about 0.9°C. Similar data for the periods 1960 and 1961 are also compared in Fig. 1. In view of the approximations made in deriving mean values and in estimating the net radiation intensity, such a degree of agreement is encouraging. It indicates the practicability of regarding the resistance as constant.

Further evidence on the effective stability of the moisture-transfer resistance is provided by figures obtained with an Australian Standard Tank, which are matched against estimated radiation intensities in Table 2. It can be seen that the median values for the six years are about 33 mm Hg.cm^2.min/cal. The comparatively low values for 1960 onwards may be connected with shifting the evaporimeter to a different site in 1960: Hounam (1961) reported that in many cases the evaporation rates are high for the first year or two after installation. However, over the period 1960-62 the resistance for the Australian Standard Tank was more constant than that for the Class A pan, as may be seen in Table 3.

Table 3 includes data from the study of evaporimeter relationships at Griffith by Fleming (1964). It can be seen that lowering the height of the Class A pan in 1961 led to a relatively high resistance (r_w) and also to a low ratio of evaporation rates.

3. THE HEAT-DIFFUSION RESISTANCE

The resistance (r_h) can be derived from equations (i) and (ii), if it is assumed that heat storage is negligible -

$$r_h = \frac{T_s - T_a}{R - LE} \qquad \ldots (x)$$

Unfortunately equation (x) inherently does not yield accurate values, since it involves differences between pairs of variables which are similar in magnitude. This emphasizes errors in estimating the water-surface temperature (T_s) and the radiation intensity (R). Consequently there is considerable scatter of the values in Fig. 2, showing monthly mean conditions for the Class A pan evaporimeter in 1960-62. The correlation coefficient is 0.67, which is highly significant, but there is an appreciable divergence of the two regression lines.

Table 1. Comparison of monthly-mean measured and calculated water-surface temperatures in a U. S. Weather Bureau Class A pan evaporimeter at Griffith, N. S. W. during 1962

	Measured Values					Calculated Values		
	Sunshine (hr)	Vapour Pressure, e_a (mmHg)	Air Temperature, T_a (°C)	Water-surface Temperature, T_s (°C)	Pan Evaporation, LE ($cal/cm^2.min$)	Radiation, R ($cal/cm^2.min$)	Resistance, r_w ($mmHg.cm^2.min/cal$)	Water-surface Temperature, T_s (°C)
January	9.4	22.1	24.1	25.6	0.32	0.31	25.0	24.6
February	11.0	20.0	22.4	23.9	0.33	0.32	26.3	22.6
March	9.1	18.3	21.0	21.7	0.25	0.22	-	20.7
April	8.6	13.4	16.1	17.2	0.15	0.14	32.3	15.1
May	6.0	9.6	10.8	11.1	0.09	0.07	-	11.2
June	5.3	9.6	10.8	10.6	0.07	0.05	-	10.9
July	5.8	8.4	8.7	8.9	0.07	0.06	27.0	8.7
August	6.9	9.1	9.9	10.0	0.11	0.10	18.2	11.5
September	8.4	11.2	12.9	13.9	0.19	0.18	18.5	15.4
October	7.7	12.4	14.9	15.6	0.22	0.22	23.2	15.8
November	10.3	17.0	19.7	20.0	0.32	0.31	29.4	19.1
December	9.0	20.0	22.3	22.8	0.35	0.31	-	22.6

Table 2. Monthly-mean data relating to the estimation of the resistance to mass-transfer (r_w) from an Australian standard tank at Griffith, N. S. W.

R is the radiation intensity (cal/cm^2.min)

LE is the energyflux involved in evaporation (cal/cm^2.min)

r_w is the estimated vapour-diffusion resistance (mmHg.cm^2.min/cal)

Year	1957			1958			1959			1960			1961			1962		
Month	R	LE	r_w	R	LE	r_w	R	LE	r_w	R	LE	r_w	R	LE	r_w	R	LE	r_w
January	0.34	0.37	-	0.33	0.33	31	0.33	0.34	37	0.28	0.31	-	0.32	0.32	40	0.31	0.28	-
February	27	26	42	27	28	38	29	30	36	26	28	-	29	32	-	0.32	30	-
March	21	21	40	20	18	-	21	18	-	21	22	38	23	22	32	22	22	32
April	14	15	37	14	14	40	16	14	-	12	15	-	12	13	29	14	14	35
May	08	09	42	07	08	33	08	09	33	07	08	25	08	10	-	07	09	-
June	05	06	67	06	06	40	05	05	43	05	07	-	05	06	25	05	07	-
July	05	05	36	06	05	45	05	06	32	05	05	26	05	06	29	06	06	31
August	10	08	-	09	08	29	10	10	34	10	07	-	11	07	-	10	10	20
September	19	15	-	17	11	-	17	14	-	16	-	-	19	13	-	18	14	-
October	26	19	-	21	16	-	21	17	-	25	-	-	28	21	-	22	16	-
November	32	28	-	26	-	-	29	30	34	29	-	-	29	22	-	31	25	-
December	30	32	-	31	31	33	28	27	29	29	30	34	33	27	-	31	29	-
median			41			36			34			30			29			31

Table 3. Water-vapour diffusion resistances (r_w) and the ratio of mean evaporation rates at Griffith, N. S. W.

Year	Resistance, r_w ($mmHg.cm^2.min/cal$)			Ratio of Mean Evaporation Rates *	Height of Class A Pan from Ground (inches)
	Aust. St. Tank	Class A Pan	Ratio		
1960	30	25	1.2	1.22	2
1961	29	29	1.0	1.12	0
1962	31	26	1.2	1.19	6

* after Fleming (1964)

The treatment of scattered results has been considered by Morgan (1960), who showed that the functional relationship lies between the regression lines and has a slope which depends on the random errors made in determining the x and y co-ordinates respectively. The data in Fig. 1 give about 1°C as the standard deviation of random errors in calculating the temperature difference in equation (x). However, it is more complicated to obtain a figure for the error in determining the sensible-heat flux (R - LE).

The sensible-heat flux error for the Class A pan can be deduced from the variability of 23 values of the term $\frac{e_{sat} - e'_a}{LE'}$ whose median was taken as the resistance (r_w). These all corresponded to values of the flux (R - LE) of 0.01 $cal/cm^2.min$ or less. The standard deviation of the 23 values was found to be 7.7 $mmHg.cm^2.min/cal$, which may be regarded as compounded of three factors - (a) the effect of wind on the resistance, (b) the error in deducing the sensible-heat flux, and (c) the permitted deviation of up to 0.01 $cal/cm^2.min$ in the relevant values of the flux (R - LE). The variation due to wind fluctuations has been quoted earlier as about 7 per cent of the value of the resistance, i.e. about 1.8 $mmHg.cm^2.min/cal$. This variation may be expressed in terms of the sensible-heat flux by means of the functional relationship in Fig. 3, which was calculated by a process of iteration, on the assumption of equal errors in the terms in both Figs. 2 and 3, using all the available values of $\frac{e_{sat} - e_a}{LE}$ and the corresponding flux (R - LE). The functional relationship shows that a variation of 7.7 $mmHg.cm^2.min/cal$ is equivalent to one of 0.054 $cal/cm^2.min$, and 1.8 $mmHg.cm^2.min/cal$ is equivalent to 0.013 $cal/cm^2.min$. Since the sum of the squares of the three individual errors equals the square of the total error, it follows that the error in deducing the sensible-heat flux is about 0.05 $cal/cm^2.min$.

The estimates of errors (i.e. 1°C and 0.05 $cal/cm^2.min$) have been applied to the results in Fig. 2 to obtain the following functional relationship -

$$(T_s - T_a) = 1.1 + 4.3\ (R - LE)\ ^\circ C \qquad \ldots (xi)$$

The separation of the line from the origin is less than the estimated errors, so equations (x) and (xi) are regarded as equivalent and the slope of the functional relationship is the heat-transfer resistance (r_h), i.e. $43^\circ C.cm^2.min/cal$.

The same procedure might be applied to monthly-mean results obtained over six years with the Australian Standard Tank at Griffith. Fig. 4 shows that the derived values are widely scattered, perhaps as a consequence of the likely thermal-storage effects as well as the errors involved in estimating radiation, accentuated by the form of equation (x). The correlation coefficient is only 0.36. However, the relationship is significant at the level of 1 in over 100 and, if the same degrees of random error are assumed to apply to both evaporimeters for the estimation of the terms in Figs. 2 and 4, the heat-diffusion resistance (r_h) for the Australian Standard Tank is deduced as $50^\circ C\ cm^2.min/cal$, though it is clear from Fig. 4 that this value is merely indicative.

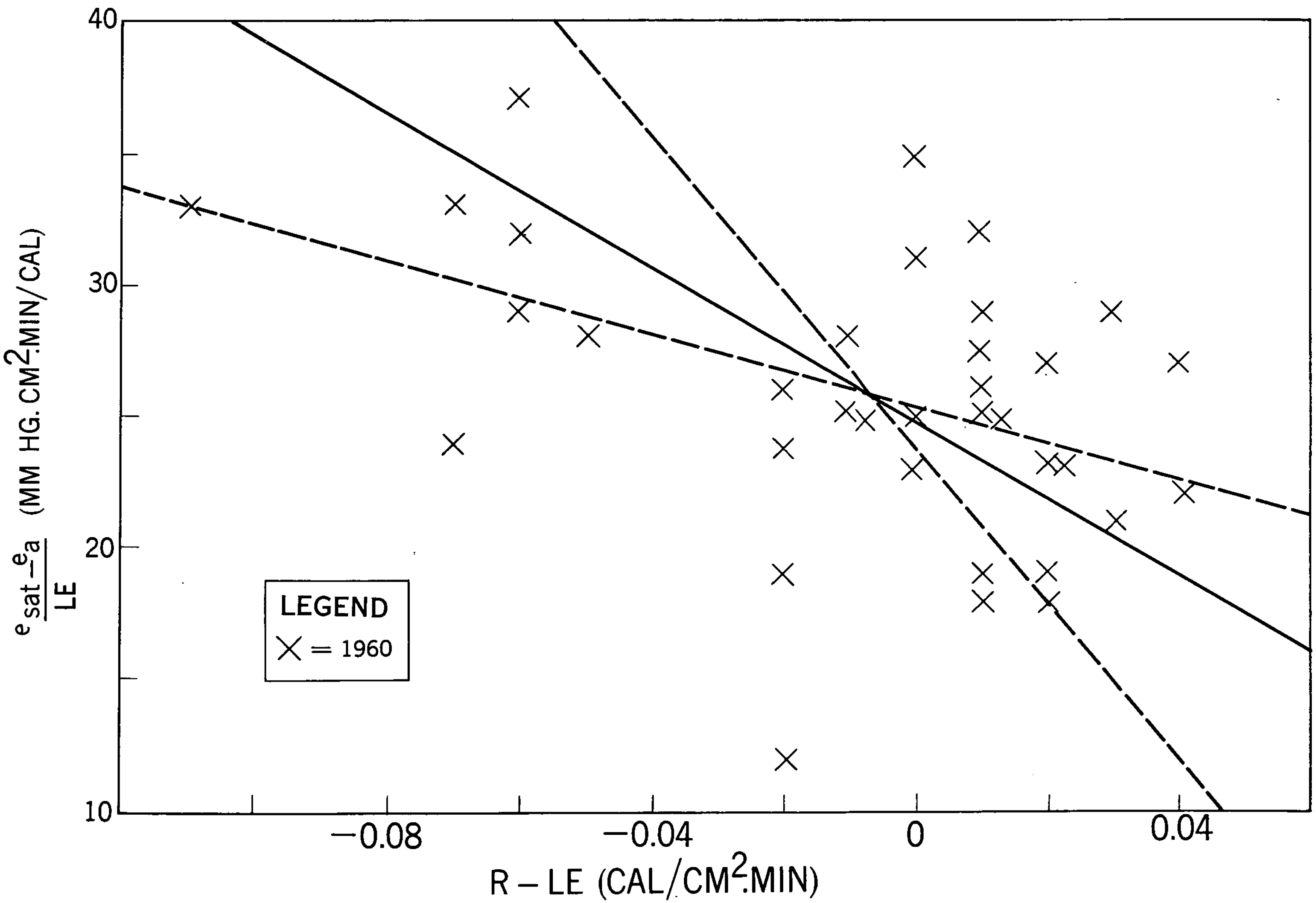

Fig. 3 Correlation of the dividend $\frac{(e_{sat} - e_a)}{LE}$ and the flux $(R - LE)$, for the case of a United States Weather Bureau Class A pan evaporimeter. The outer lines are regression lines and the inner line expresses the derived functional relationship.

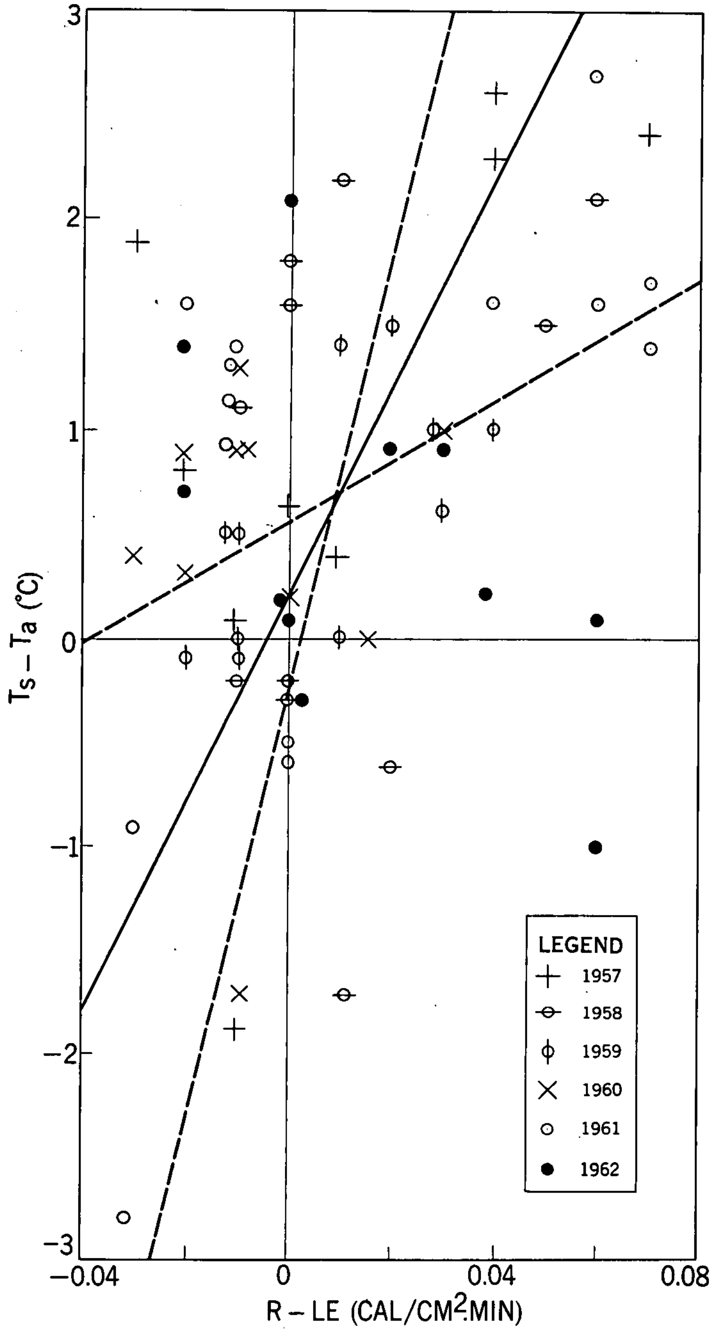

Fig. 4 Correlation of estimated monthly – mean values of the nominal sensible – heat flux (R – LE) from the water in Australian Standard Tank evaporimeter, and the difference between the temperatures of the water surface (T_s) and the air (T_a). The outer lines are regression lines and the inner line expresses the derived functional relationship.

4. DISCUSSION

The derived resistances are given in Table 4. It can be seen that the ratios of the approximate resistances exceed the value of 0.49 mmHg/^{o}C customarily taken as the psychrometric constant. In other words, the evaporimeters appear to lose heat more readily than they lose moisture. Two explanations are possible. Either the eddy diffusivities for heat and moisture differ, or heat is lost through the walls and base of the evaporimeters. Kohler et al. (loc. cit.) have shown that the latter certainly occurs in the case of a U.S. Class A pan evaporimeter, where the total heat loss may be 140 per cent of that from the water surface alone, i.e. the resistance ratio may be 0.69 mmHg/^{o}C. This adequately explains the difference between the psychrometric constant and the ratios in Table 4, so there is no need to infer appreciable differences between the mean eddy diffusivities of heat and water-vapour from the water surfaces of the evaporimeters.

Table 4. Derived diffusion resistances

Evaporimeter	r_w (mmHg. cm^2.min/cal)	r_h (^{o}C. cm^2.min/cal)	r_w/r_h (mmHg/^{o}C)
U.S. Class A	26	43	0.60
Aust. Stand. Tank	33	50	0.66

The indication of similar diffusivities can be seen from Figs. 2 - 4 to be based on data which must be improved before the point is established satisfactorily. It is desirable that evaporation records extending over a long period should be used and values of net radiation intensity should be measured, not estimated.

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