EVAPORATION MEMORANDUM No. 43

THE PROBABLE EFFECT OF SOIL HEAT FLUX ON POTENTIAL EVAPORATION

by

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1. INTRODUCTION

Penman's formula for Potential Evaporation (PE) underestimates the measured PE in the winter and overestimates it in the summer (Wales-Smith, 1975). So Penman's equation was modified (Wales-Smith, 1976) using Thom and Oliver's improved aerodynamic term (1977) and by adjusting the long-wave term. After these modifications had been incorporated, the calculated PE was compared with measured PE from evaporimeters between 1964 and 1970. However, the modified form of Penman's equation still underestimated the PE in the winter and overestimated it in the summer by up to several mm per month.

This discrepancy was found to be approximately in phase with the average seasonal pattern of soil temperature measured at a depth of 30 cm. Since the change of this temperature with time is a measure of the quantity of heat entering and leaving the soil surface, the discrepancy between actual and calculated PE may be because the soil heat flux (SHF) has not been included in the modified Penman formula. Because this formula does not allow for heat entering the soil in the summertime, too much energy is available for evaporation and so the calculated PE is too large. Conversely, in the wintertime, Penman's formula does not allow for any heat coming out of the soil and so the calculated PE is too small.

This hypothesis seems very plausible because Roach (1955) found that the SHF measured at Kew at a depth of 6 cm between May 1953 and April 1954 showed a similar phase and magnitude to the discrepancy between calculated and measured PE. However, one year's data is not sufficient to provide adequate proof - several years of data are really required. Furthermore, it would be useful to have SHF measurements at different depths so that the SHF near the surface can be estimated by extrapolation.

The aim of this investigation is therefore to determine, by using several years of data, whether in fact the SHF can account for the difference between measured and calculated PE. SHF data are somewhat scarce but measurements were available from the Meteorological Research Unit at Cardington, Bedfordshire, and these data have been extracted and processed.

2. DATA EXTRACTION

Measurements of SHF have been made at Cardington using flux plates inserted at two different depths in the soil. From July 1966 to September 1967, (Period I), SHF was measured at a depth of 4 cm and from September 1972 to May 1975 (Period II) the SHF was measured at 4 and 8 cm.

During Period I, the SHF was available directly in flux units of mW cm^{-2} but the data for Period II had to be extracted from Kent Recorder charts and converted from mV to mW cm^{-2}. [There was some doubt about which of two conversion factors should be applied between September 1972 and April 1973. However comparisons between the 4 and 8 cm SHF indicate that the correct conversion factors for the whole of Period II are as follows:

For the 4 cm plate, 1mV = 7.04mW cm^{-2}

For the 8 cm plate, 1mV = 5.98mW cm^{-2}]

In order to obtain a reliable mean SHF for each month at both depths, readings were extracted eight times each day at 00, 03, 06, 09, 12, 15, 18 and 21 GMT - and the mean monthly SHF was computed by simply averaging all the readings obtained during each month. During the extraction, it was found that during Period II, there were some days when no reading was available at the times indicated above owing to breaks in the Kent Recorder chart record. If the breaks were short (e.g. only one or two hours), the reading at the required time was estimated by simple interpolation but if the gaps were longer, and interpolation was not possible, the reading was classified as missing. Inaccuracies also arose owing to the varying thickness of the Kent Recorder traces and because the time marks were sometimes missing, but every effort was made to reduce errors to a minimum.

Each monthly SHF and the corresponding number of missing observations are listed in Table 1 and the values plotted in Fig 1. If the equivalent of more than five days data per month was missing, the corresponding monthly SHF was not plotted.

3. ANALYSIS OF MONTHLY SHF

(a) General Description.

Fig 1 shows that the SHF at depths of 5 and 10 cm varies in an approximately sinusoidal fashion during the year with maximum upward fluxes in the late autumn - usually November - and maximum downward fluxes in the summer - usually in June or July. The months in which the maxima occur vary from year to year and depend upon the year to year variability of the weather at Cardington. Roach found a similar annual pattern of SHF but his maximum upward flux occurred in January and maximum downward flux in May. The maximum upward heat flow in January resulted from the exceptional mildness of November and December 1953.

The magnitudes of the fluxes also vary from one year to the next. Typical maximum upward fluxes at 4 cm depth range between 0.5 and 1.3 $mWcm^{-2}$ (equivalent to between 5 and 14 mm water evaporated per month) while maximum downward fluxes vary between 0.9 and 1.7 $mW\ cm^{-2}$ (10 to 18 mm water evaporated per month). The magnitudes of the SHF at 8 cm are generally smaller than at 4 cm indicating flux convergence between 4 and 8 cm in the winter and flux divergence in the summer.

There were, however, some months when this general seasonal trend was not followed.

(b) Exceptions to the general annual SHF pattern.

(i) December 1974

In the Decembers of 1966, 1972 and 1973, the SHF at both levels was quite definitely upward with magnitudes of between 0.3 and 0.5 $mW\ cm^{-2}$. However, in December 1974, the 4 cm SHF changed its sign from upward to downward. Unfortunately, it is not possible to support this reversal using the SHF at 10 cm because too many readings were missing at this level. It would be tempting to treat these results as being suspect but perhaps they occurred because the weather conditions at the end of 1974 were exceptional.

Table 2 shows the monthly mean dry-bulb temperature at Cardington using the readings at 03, 09, 15 and 21 GMT in October to December 1966, 1972, 1973 and 1974. November and December 1974 were quite clearly much warmer than the corresponding months in 1966, 1972 and 1973 and December 1974 was about 3°C warmer than the average of the three other Decembers. So more heat than usual may have been available at the surface in December 1974 and the recorded reversal in SHF may have been real. Indeed, the 30 cm soil temperatures also support this view. The change in 30 cm temperature between October and December 1966, 72 and 73 is 6.9, 4.8 and 5.2°C respectively (Table 3). However, the corresponding change in 1974 is only 2.3°C and the change from November to December is merely 0.3°C ! These results suggest that the soil at 30 cm lost far less heat in late 1974 compared with previous years and this agrees with the observed reversal of SHF nearer the surface. The observed fluxes have therefore been treated as correct.

(ii) <u>April 1975</u>

In the Aprils of 1967, 1973 and 1974, the 4 cm SHF varied between 0.3 and 0.6 mW cm^{-2} (downwards) but in April 1975, it reached as high as 1.7 mW cm^{-2} (downwards). This very large flux is supported by an unusually high 8 cm SHF of 1.6 mW cm^{-2}. The mean dry-bulb temperature in April 1975 at Cardington was 8.2°C compared with only 7.7, 7.3 and 7.2°C in the other three Aprils. More heat was therefore available at the surface in April 1975 and so the downward SHF could indeed have been greater.

So far, the observed fluxes have only been justified subjectively. More rigorous, quantitative explanations could be provided by extracting the monthly mean soil temperatures near the soil surface. Since

$$SHF \propto K \frac{dT}{dz} \qquad , \qquad (1)$$

where K is the thermal conductivity of the soil and $\frac{dT}{dz}$ is the vertical temperature gradient, the direction of the flux can be readily determined by taking the difference between, say, the soil temperatures at 4 and 8 cm. The reversal of the SHF in December 1974 can then be verified. If magnitudes of SHF are required from the soil temperatures, Equation (1) can be used if a suitable estimate can be made of the soil thermal conductivity which is a function of the soil type, air and water content (see e.g. Van Wijk and De Vries, 1963).

(c) Pattern of mean monthly SHF.

An average SHF was calculated for each named month using the data in Fig 1 and the results are shown in Fig 2. (Note that the mean 8 cm flux was not necessarily calculated using the same months as the mean 4 cm flux so the two flux curves in Fig 2 are not directly compatible). The mean monthly SHF at both depths vary approximately sinusoidally during the year with maximum mean downward fluxes at 4 and 8 cm of 1.2 and 0.9 mW cm^{-2} (equivalent to 13 and 10 mm water evaporated per month) in June and maximum mean upward fluxes of 0.6 and 0.7 mW cm^{-2} (7 and 8 mm water per month) in November.

(d) Comparison between SHF and discrepancy between observed and calculated PE.

How do these fluxes compare with the difference between the observed and calculated PE (Δ PE)? Fig 2 shows that the monthly mean SHF and Δ PE are closely correlated. Of course, it must be appreciated that the Δ PE and SHF data came from different years so resultant differences between the two parameters may arise. Even so, it is encouraging to see that their magnitudes and phases are very similar.

The main differences between the SHF and Δ PE are as follows:

(i) Whereas the value of Δ PE summed over the year is zero, the corresponding SHF is slightly negative, implying a net warming of the soil.

(ii) In March, Δ PE is nearly 10 mm month^{-1} lower than the mean monthly SHF (converted to mm month^{-1}).

(iii) Except for March, the monthly mean Δ PE curves (Fig 2) lies above the SHF curve by a few mm month^{-1}.

In order to resolve these differences, Δ PE and SHF should be compared using data for the <u>same period</u> for, as we have seen from Fig 1, the SHF during any named month may vary considerably from year to year according to the weather conditions. As SHF data are scarce, perhaps it would be worthwhile concentrating only on the periods shown in Fig 1 and, if possible, 1976. In addition, it would be better to use values of Δ PE and SHF measured at the <u>same location</u>. If, after these improvements in the data analysis, there are still differences, the significance of these differences should be determined by calculating the scatter of each monthly mean value of Δ PE and SHF. The uncertainty of each value of Δ PE and the experimental errors in measuring SHF using flux plates (e.g. Monteith 1958) should also be taken into account.

If, at this stage, the differences are found to be significant and in the same sense as those shown in Fig 2, then perhaps the following discussion may be pertinent. The excess of downward over upward flux shown in Fig 2 was due partly to the apparent anomaly at the end of 1974 and early 1975 (Fig 1) when downward SHF, apparently unusual for this season, occurred. However, Fig 1 demonstrates that there was an excess downward flux at other times like, for example, between July 1966 and July 1967. The validity of this measured excess downward flux is supported by a temperature rise at 30 cm from 16.1 to 17.6^{o}C between July 1966 and July 1967. Between Autumn 1972 and Autumn 1974, the overall excess of downward above upward flux at 4 cm was due mainly to the very large downward SHF in June 1973. In fact, from September 1972 to September 1974, the average excess downward flux at 5 cm was $\sim$0.05 mW cm^{-2}. At 10 cm, where the SHF in June 1973 was much smaller, there was an excess upward flux over the same period of $\sim$ 0.03 mW cm^{-2}. These values are about an order of magnitude smaller than the individual monthly fluxes and, bearing in mind the probable errors in the flux plate measurements, it is probably not prudent to derive a great deal from these figures.

The difference between Δ PE and SHF in March is very striking. Fig 2 shows that there is a sudden jump in Δ PE but that the SHF changes very smoothly from one month to the next. It seems, therefore, that the cause of the large difference is probably due to the apparent large, negative value of Δ PE (i.e. the calculated PE is much larger than the measured PE). What is so special about March compared with other months of the year? At this time of year, the topsoil normally begins to dry out and so latent heat must be supplied near the surface to evaporate the soil water. This resulting cooling is not taken into account in Penman's formula and the calculated PE may be overestimated. It would be interesting to test this idea by finding out whether a large Δ PE occurs each March or whether the large value in Fig 2 is the result of only a few anomalous Marches. In addition, is there any correlation between large ΔPE and the occurrence of the first SMD of the year and are the orders of magnitude reasonable?

The results shown in Figs 1 and 2 indicate the annual variation of SHF measured at depths of 4 and 8 cm. In order to estimate the contribution of SHF to PE, the SHF near rather than below should be calculated. In general, the magnitude of the individual net monthly SHF is larger at 4 cm than at 8 cm (see Fig 1) and simple extrapolation would suggest that the flux near the surface will be even larger. For example, in the period September and February beginning in 1973 and 1974, the mean upward 4cm and 8 cm fluxes are 0.487 and 0.426 mW cm^{-2} respectively. Using logarithmic extrapolation (recommended by Richards - personal communication), the SHF at a depth of 1 cm would be 0.6 mW cm^{-2} which is 0.1 mW cm^{-2} higher than the 4 cm flux. This modification would help to reduce any difference between Δ PE and SHF in the winter months like that shown in Fig 2 but would make the difference larger in the summer !

We must not forget that the differences we are attempting to resolve are considerably smaller than the magnitudes of the heat gained and lost by radiation. Indeed, the SHF itself is very much smaller than values of the Penman radiation terms ! Furthermore, there may be other quantities included in estimating PE with errors of a similar magnitude and so, bearing in mind the likely errors in measured SHF, extensive work in refining results may not be worthwhile.

4. ESTIMATION OF SHF OVER GREAT BRITAIN

So far, SHF measurements at Cardington only have been considered. How can SHF be estimated in other parts of the country? Unfortunately, present measurements of SHF are few and far between and would be inadequate for calculating the SHF contribution to the PE over the whole country. Reference really needs to be made to a soil variable measured over a network like, for example, the soil temperatures at depths of 30 and 100 cm.

If the change in 30 cm soil temperature is assumed to represent the quantity of heat entering and leaving unit area of a soil block, then

$$SHF \propto \frac{dT_{30}}{dt} \qquad (2)$$

Where T_{30} is the 30 cm soil temperature and t is time.

We have at our disposal monthly means of T_{30}. So, to a good approximation, the SHF in month M should be given by (omitting the subscript $_{30}$)

$$SHF \propto \left[\frac{(T_{M+1} + T_M)}{2} - \frac{(T_M + T_{M-1})}{2} \right]$$

which leads to

$$SHF \propto (T_{M+1} - T_{M-1})$$

where T_{M+1} is the 30 cm temperature in month M+1, T_{M-1} the temperature in month M-1 and T_M the temperature in month M.

Let $(T_{M+1} - T_{M-1})$ be ΔT_M for simplicity.

Fig 2 shows how ΔT_M (calculated using the monthly values of T_{30} in the Monthly Weather Report) varies during the year. As expected, ΔT_M is closely correlated with SHF but appears to be approximately one month ahead of the SHF. For instance, the summertime maximum of ΔT_M occurs in May whereas the corresponding maximum SHF occurs in June. This phase difference may be because of the approximations made in Equation (2). In actual fact, if we consider a layer of soil, thickness ΔZ and heat capacity C, with its centre of the layer at 30 cm, then the heat fluxes entering the top (SHF_{top}) and leaving the bottom (SHF_{bott}) of the layer are related by the equation

$$SHF_{top} - SHF_{bott} = C \times \Delta Z \quad \frac{dT}{dt}_{30}$$

Now SHF_{bott} will be a function of the temperature difference between 30 cm and 100 cm (plotted in Fig 2) which reaches a maximum in June. So if

$$\left\{ (SHF_{top})_{June} - (SHF_{top})_{May} \right\} < \left\{ (SHF_{bott})_{June} - (SHF_{bott})_{May} \right\},$$

then the quantity $\frac{dT}{dt}_{30}$ will be lower in June than in May and would give the observed behaviour of ΔT_M. A reverse argument can be applied for the behaviour of ΔT_M in November.

It must be emphasized that the above arguments are all very crude and qualitative and need to be justified by quantitative proofs, perhaps using some more data from Cardington where more thorough studies of soil parameters are currently in progress. Even so, ΔT_M could provide a useful basis for estimating SHF in other parts of the country by virtue of Equation (2). A word of caution is, however, necessary. The constant of proportionality in Equation (2) contains the soil heat capacity which not only varies with soil type but also water content. So, with a given amount of heat, the soil temperature will change by a smaller amount in winter (when the heat capacity is large) than in summer (when the heat capacity is small). Furthermore, during a given season of the year, the soil may be wetter in the north of the U.K. than in the south so the relationship between SHF and ΔT_{30} may also depend on latitude. Ideally, therefore, the relationship should be tested in other parts of the country, using a soil type data set and by varying the soil water content.

5. CONCLUSION

From an anlysis of Cardington SHF data, it appears that the established discrepancy between measured and calculated monthly PE (Δ PE) may arise partly because the positive and negative soil heat flux (SHF) contribution to PE has so far been neglected. There are still some fairly minor differences between measured and calculated PE, even after SHF has been included, but these could possibly be reduced by an improved analysis of Δ PE and SHF data for identical periods. If, subsequently, they are still evident, they will probably be much smaller than other uncertainties in estimating PE so that additional work to eliminate them may not be worthwhile. A method of estimating the contribution of SHF over Great Britain has also been proposed, using 30 cm temperatures, but account must be taken of the soil heat capacity.

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REFERENCES

MONTEITH J L	1958	The heat balance of soil beneath crops. U.N.E.S.C.O. Arid Zone Res 11 Climatology and Microclimatology. Proc. Canberra Symp., pp 123-127.
ROACH W T	1955	Measurements of atmospheric radiation and the heat balance at the ground at Kew. May 1953-May 1954. London, Met Office, Met.Res.Comm. Rep No. 936.
THOM A S and OLIVER H R	1977	On Penman's equation for estimating regional evaporation. Quart. J.Roy.Met.Soc. Vol 103 pp 345-358.
VAN WIJK W R and DE VRIES D A	1963	Periodic temperature variations in a homogeneous soil. Physics of Plant Environment (North-Holland) p.102.
WALES-SMITH B G	1975	The quality control of evaporimeter data. London, Met.Office, Evap.Mem No. 37 (Unpubl)
WALES-SMITH B G	1976	Implications of recent researches for changes in the Penman formula for regional potential evaporation. (Unpubl).

TABLE LEGENDS

Table 1	Monthly soil heat flux at Cardington. ↑ denotes an upward flux, ↓ denotes a downward flux.
Table 2	Monthly mean dry bulb temperature at 03, 09, 15 and 21 GMT at Cardington.
Table 3	Monthly mean 30 cm soil temperatures measured at Cardington.

TABLE 1 (Cont)

YEAR	MONTH	SOIL HEAT FLUX ($mW\ cm^{-2}$)		NUMBER OF MISSING OBSERVATIONS	
		4 cm	8 cm	4 cm	8 cm
1973	Jul	0.514 ↓	0.531 ↓	0	0
	Aug	0.691 ↓	0.375 ↓	0	0
	Sep	0.089 ↑	0.090 ↑	0	0
	Oct	0.848 ↑	0.724 ↑	0	0
	Nov	1.133 ↑	0.961 ↑	0	0
	Dec	0.504 ↑	0.449 ↑	0	0
1974	Jan	0.200 ↑	0.203 ↑	6	6
	Feb	0.228 ↑	0.222 ↑	0	0
	Mar	0.231 ↓	0.007 ↓	0	0
	Apr	0.572 ↓	0.095 ↓	0	0
	May	0.801 ↓	0.479 ↓	15	15
	Jun	0.916 ↓	0.824 ↓	0	0
	Jul	0.480 ↓	0.393 ↓	0	0
	Aug	0.506 ↓	0.206 ↓	0	0
	Sep	0.079 ↑	0.268 ↑	0	0
	Oct	0.341 ↑	0.549 ↑	0	18
	Nov	0.018 ↑	0.351 ↑	0	28
	Dec	0.250 ↓	0.144 ↑	0	137
1975	Jan	0.189 ↓	-	0	-
	Feb	0.014 ↓	-	0	-
	Mar	0.045 ↑	1.110 ↑	0	85
	Apr	1.625 ↓	1.190 ↓	0	0
	May	0.519 ↓	0.342 ↓	0	3

TABLE 1. MONTHLY SOIL HEAT FLUX AT CARDINGTON

YEAR	MONTH	SOIL HEAT FLUX † ($mW\ cm^{-2}$)		NUMBER OF MISSING OBSERVATIONS	
		4 cm	8 cm	4 cm	8 cm
1966	Jul	0.675 ↓	–	1	–
	Aug	0.443 ↓	–	0	–
	Sep	0.199 ↓	–	0	–
	Oct	0.174 ↑	–	0	–
	Nov	0.511 ↑	–	0	–
	Dec	0.278 ↑	–	2	–
1967	Jan	0.110 ↑	–	2	–
	Feb	0.011 ↓	–	0	–
	Mar	0.262 ↓	–	0	–
	Apr	0.608 ↓	–	25	–
	May	1.044 ↓	–	0	–
	Jun	1.064 ↓	–	0	–
	Jul	1.505 ↓	–	0	–
	Aug	0.430 ↓	–	0	–
	Sep	0.230 ↓	–	91	–
1972	Sep	0.490 ↑	0.343 ↑	0	0
	Oct	0.386 ↑	0.269 ↑	2	2
	Nov	0.829 ↑	0.779 ↑	0	0
	Dec	0.470 ↑	0.487 ↑	0	0
1973	Jan	0.450 ↑	0.408 ↑	31	31
	Feb	0.217 ↑	0.178 ↑	0	0
	Mar	0.022 ↑	0.015 ↑	3	3
	Apr	0.328 ↓	0.232 ↓	0	0
	May	1.061 ↓	0.634 ↓	0	0
	Jun	1.737 ↓	0.951 ↓	0	0

† ↑ denotes an upward SHF

↓ " a downward "

TABLE 2: MONTHLY MEANS OF DRY BULB TEMPERATURES AT 03,09, 15 AND 21 GMT AT CARDINGTON

MONTH	1966	1972	1973	1974
OCT	10.7	10.6	8.8	7.2
NOV	5.5	6.0	5.3	7.0
DEC	5.3	5.8	4.9	8.1

TABLE 3: MONTHLY MEANS OF 30CM SOIL TEMPERATURES MEASURED AT 09 GMT AT CARDINGTON

MONTH	1966	1972	1973	1974
OCT	12.3	11.0	11.0	9.4
NOV	7.5	7.8	7.2	7.4
DEC	5.4	6.4	4.8	7.1

FIGURE LEGENDS

Fig 1 Monthly soil heat flux (SHF) at Cardington at depths of

4 cm o———o

8 cm +......+

between (i) July 1966 and August 1967;

(ii) September 1972 and May 1975

Fig 2 (a) A comparison between (i) mean monthly SHF at Cardington at depths of

4 cm o———o

and 8 cm +.....+

with (ii) the mean monthly difference between calculated and measured potential evaporation (PE) at Kew between 1964 and 1970.

X--------X

An upward SHF and an excess of measured over calculated PE are both shown positive.

(b) (i) o———o Mean monthly change of 30 cm soil temperature with time (ΔT_M) at Cardington (positive values are below the x axis)

(ii) x-.-.-.x Mean monthly difference of soil temperature between 30 and 100 cm* $\left(\frac{dT}{dz}\right)$. If the 30 cm temperature is greater, the point lies below the x axis.

[* NB. Before October 1972 the temperature was measured at 4 feet instead of 100 cm]

Fig 1.

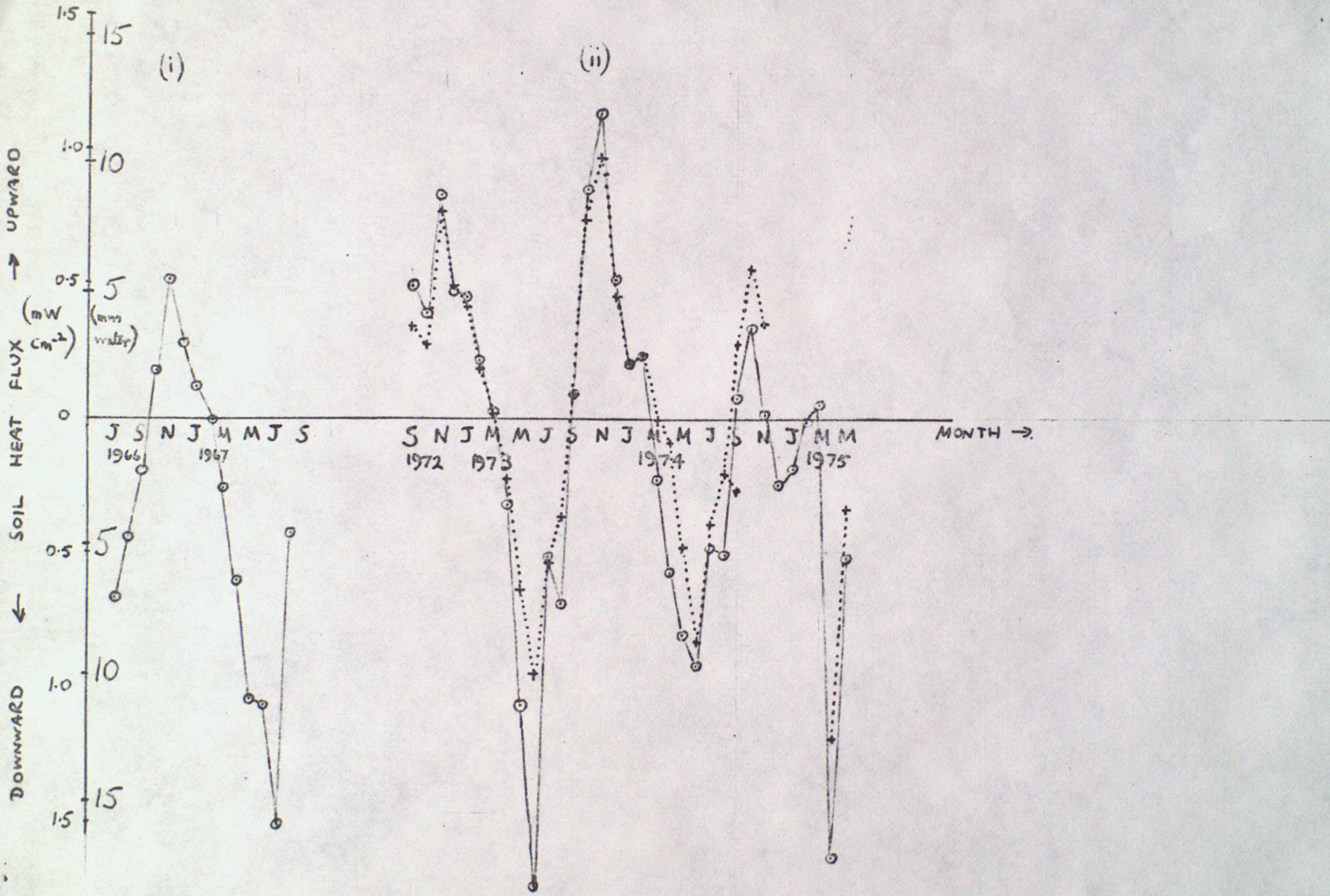
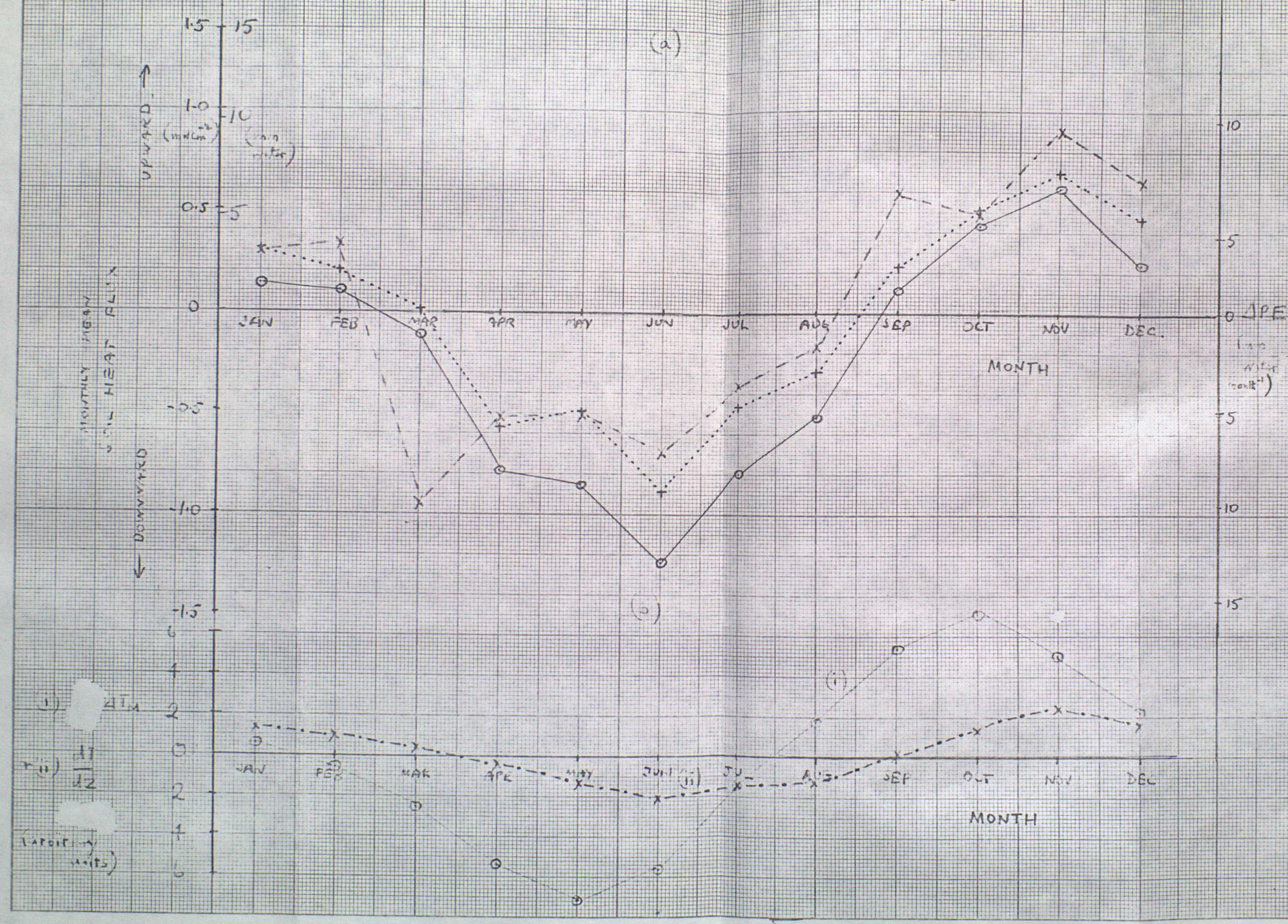

DOWNWARD ← SOIL HEAT FLUX → UPWARD
(mW cm⁻²)
(mm water)
1.5
1.0
0.5
0
15
10
5
(i)
(ii)
J S N J M M J S
1966
1967
S N J M M J S N J M M J S N J M M
1972
1973
1974
1975
MONTH →

Fig. 2



(a)
(b)
MONTH
MONTH
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
UPWARD
DOWNWARD
MONTHLY MEAN
HEAT FLUX
JPE