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Observations of soil heat flux at Pune using a heat flux plate

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ABSTRACT. Measurements of soil heat flux were made over bare black cotton soil at Pune in the period June 1976 to February 1977, using a soil heat flux plate. Hourly values of soil heat flux from 00 to 24 LAT are presented for selected days typical of the monsoon, post-monsoon and winter seasons. The diurnal variation is generally characterised by a cross-over from negative to positive values at 07 hr, occurrence of maximum around noon and return to negative values between 16 and 18 hr. The effects of rainfall, cloudiness and soil moisture on the soil heat flux are discussed.

1. Introduction

The evapotranspiration process depends upon, besides other factors, the availability of heat to satisfy the latent heat requirements. Numerous studies have been made to investigate the nature of the radiation balance at the surface. Many of them are, however, confined to the solar and infra-red radiation components which are relatively easy to determine. Much less is known about the absorption and conduction of heat by the soil and the exchange of heat between the soil and the atmosphere. The partitioning of net radiation into latent and sensible heat components is given by :

$$R_{\text{net}} = S + L_H + S_H \tag{1.1}$$

where R_{net} is the net flux at the earth's surface, S the soil heat flux, L_H the latent heat flux and S_H the sensible heat flux from the soil to the atmosphere. The generally practised neglect of the soil heat flux term in the use of the energy balance equation is not agronomically justified in view of associated sub-soil migration of moisture.

2. Measurement

Heat conduction in the soil is governed by Fourier's law

$$S = -\lambda \cdot \nabla T \tag{2.1}$$

The uni-dimensional form is:

$$S = -\lambda \frac{\partial T}{\partial z} \tag{2.2}$$

where S is the soil heat flux, λ the thermal conductivity of the soil and $\partial T/\partial z$ the soil temperature gradient along the vertical. Eqn. (2.2) has been used to derive the soil that flux from soil temperature measurements (*e.g.*, Van Wijk 1965, Subrahmanyam and Ratnam 1970) and more recently in computer simulation of soil-water relationships (Hillel 1977).

Eqn. (2.2) also forms the basis for direct determination of soil heat flux using what is known as a soil heat flux plate (Deacon 1950). This essentially consists of a small thin disc enclosing a thermocouple arrangement which measures the temperature difference across its plane parallel surfaces. In practice, such a plate is embedded in the soil, near the soil surface, in a horizontal position. The transducer output is high enough to be fed to a potentiometric recorder in continuous operation. The small dimensions of the plate ensure a minimum disturbance to the natural flow of moisture in the soil. The thermal conductivity of the plate should ideally be the same as that of the soil. This may not, however, always be true in practice. Errors may also be introduced because of poor contact between plate and soil or displacement of the plate by growing roots, earthworms, etc. The latter can be prevented by mounting the plate in a suitable frame. Because of its simplicity and convenience, the flux plate method is favoured (Biscoe *et al.* 1977).

Continuous measurements of soil heat flux by the plate method were made over bare black cotton soil at the Central Agrimet. Observatory, Pune during the period June 1976 to February 1977. The plate used had a thickness of 2.6 mm, diameter 25 mm and output 6.57 mm/cal/cm^2/min. The depth of insertion was 0.5 cm below the soil surface. Some typical case studies based on the hourly and daily soil heat flux are presented and discussed below.

TABLE 1

Soil moisture (Percentage by wt.) at various depths on selected days

Depth (cm)	Monsoon season (Jul 1976)			Post-monsoon season (Oct 1976)			Winter season (1977)		
	8 Jul	15 Jul	22 Jul	7 Oct	14 Oct	21 Oct	27 Jan	3 Feb	10 Feb
7.5	20.6	25.3	26.7	20.3	21.6	18.6	5.4	7.1	7.9
15	19.4	24.7	26.8	20.4	18.3	17.6	14.0	8.9	8.3
22.5	19.6	23.9	26.3	27.3	19.1	20.8	15.6	15.6	16.0
30	14.5	23.1	26.3	17.9	18.7	16.5	16.1	—	19.6
45	18.0	15.2	24.9	20.0	20.9	17.6	17.1	18.5	17.4

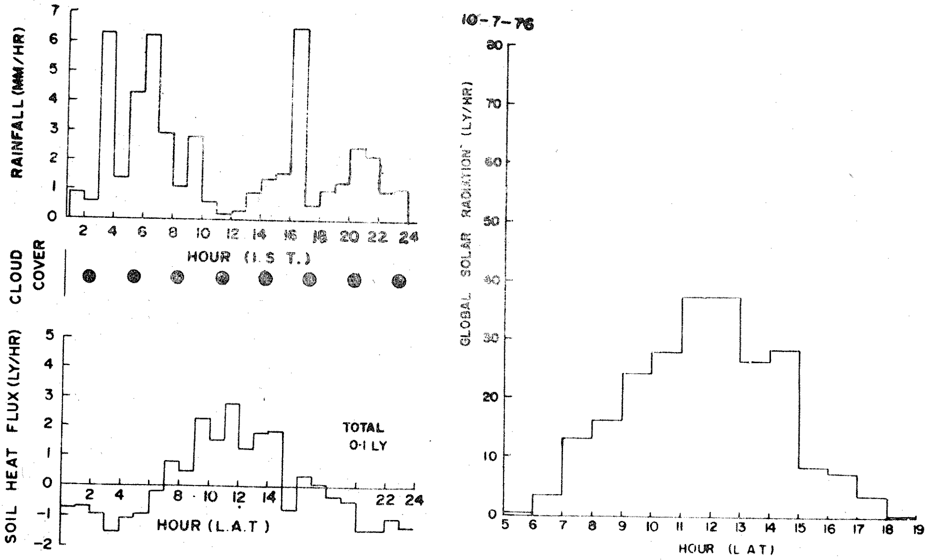

Fig. 1. Monsoon season

3. Results

Six typical situations, two each from the monsoon, post-monsoon and winter seasons, are depicted in Figs. 1 to 6. Hourly values of soil heat flux from 00 to 24 LAT are shown in each figure and the 24-hour total is given. The fraction of the sky covered by clouds as observed at 3-hourly intervals is also marked. In order to provide a better indication of the sky condition and the energy input to the soil, curves of hourly global solar radiation are given for the daylight hours. These were constructed from the continuous records of a Moll-Gorczynski pyranometer. For the monsoon season, hourly amounts of rainfall as measured with a self-recording raingauge are shown as well. Since IST and not LAT is used for rainfall, the x-axis is shifted suitably to the left to maintain a correspondence with the x-axis of the soil heat flux curve. Soil heat flux is regarded as positive when it is directed into the soil and negative in the opposite direction. Relevant soil moisture data (on a percentage by weight basis) are given in Table 1. These are routine measurements made once a week involving sample extraction by an auger and drying in an oven.

4. Discussion

4.1. *Diurnal and seasonal variation*

The diurnal variation of soil heat flux at Pune is characterised by a cross-over from negative to positive values at 07 LAT, occurrence of maximum during the hour ending at local noon and a return to negative values between 16 and 18 LAT. This trend is quite similar to that of the net flux at the surface, soil heat flux and net flux being generally well-correlated (Idso *et al.* 1975). However, the diurnal range of soil heat flux, and hence the 24-hour sum, varies considerably with season. This is the combined effect

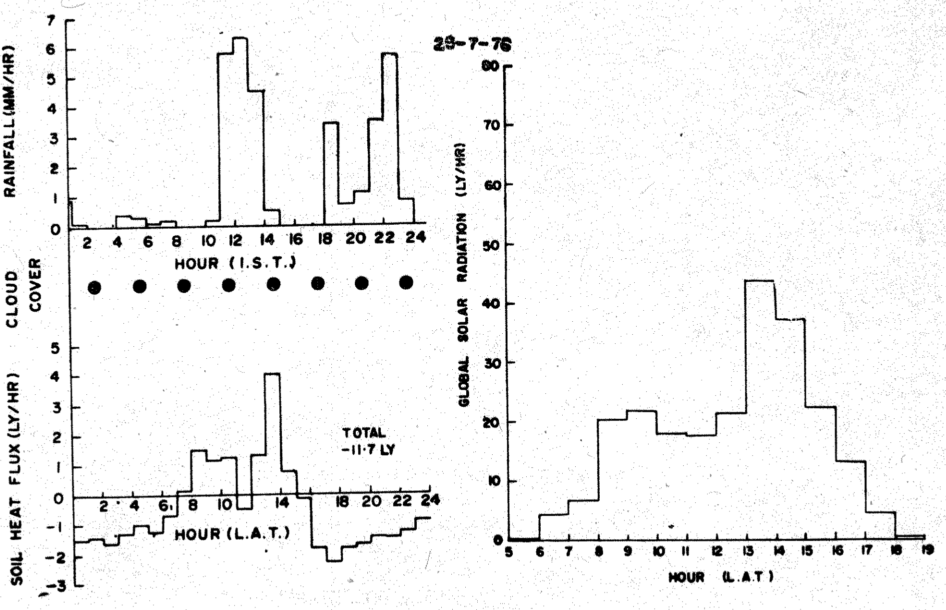

Fig. 2. Monsoon season

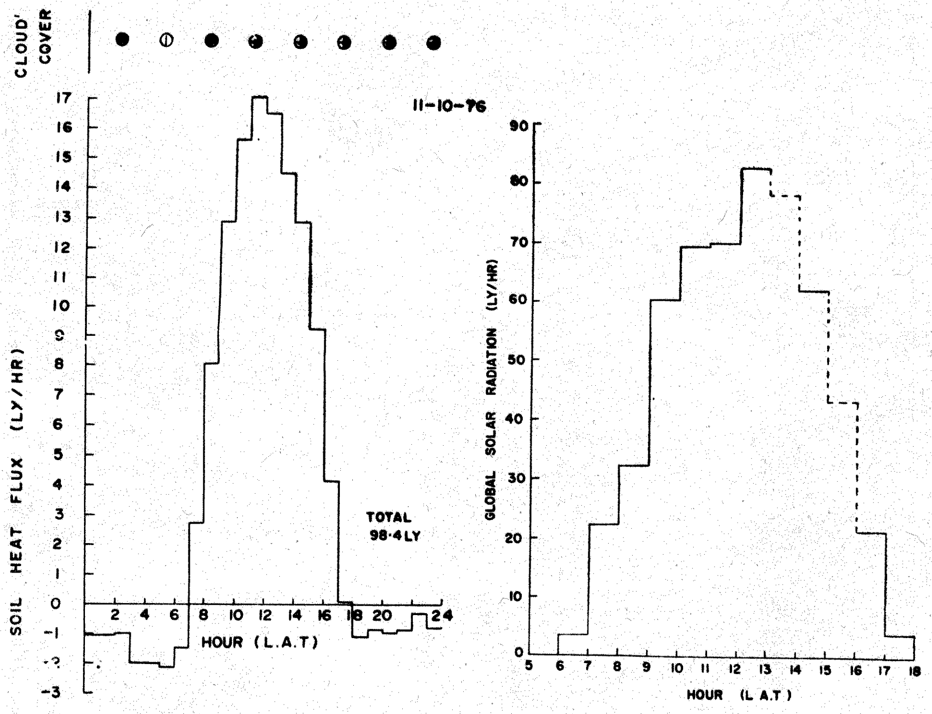

Fig. 3. Post-monsoon season

of the global solar radiation received by the surface and the moisture status of the soil. Here, the former alters the soil temperature profile, whereas the latter regulates the values of λ. In addition, irregularities in the shape of the diurnal curve are introduced as a result of rainfall and changes in the cloud cover.

Out of the two monsoon cases, the one on 10 July 1976 (Fig. 1) was marked by almost continuous rain and a stratus-altostratus overcast. Soil heat flux, under these conditions, could reach a value of only 2.8 ly/hr in the hour preceding noon. The diurnal range is as low as 4.3 ly/hr and the 24-hour sum is 0.1 ly, or almost

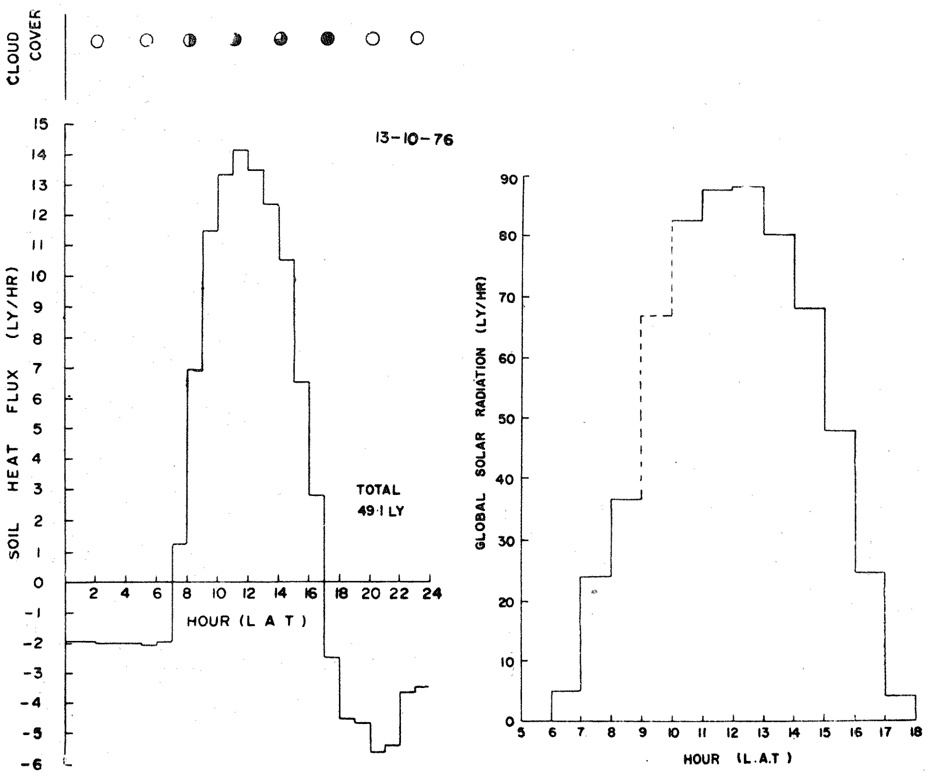

Fig. 4. Post-monsoon season

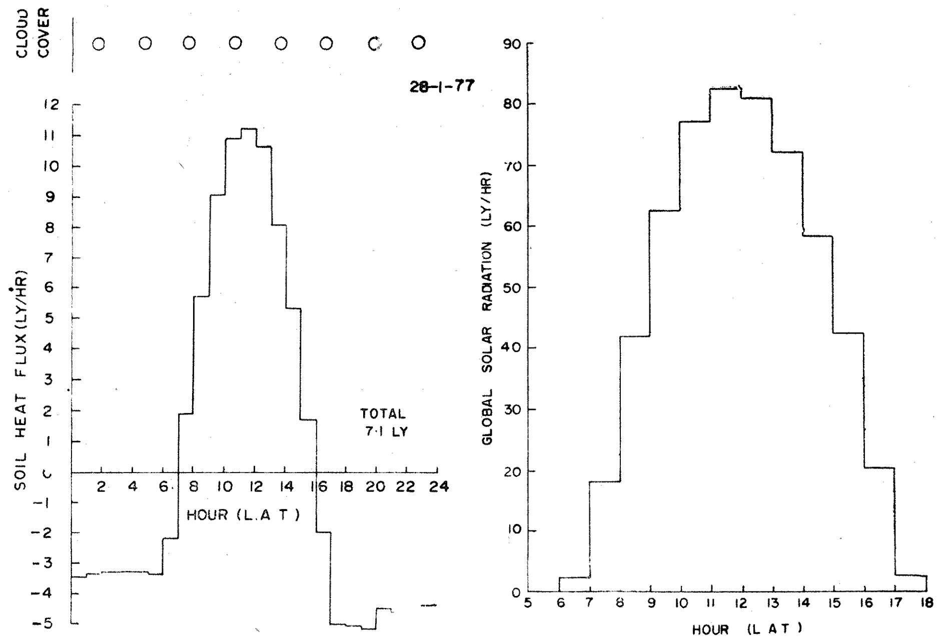

Fig. 5. Winter season

zero. Again, on 29 July 1976 (Fig. 2) there was good rain and a stratus-altostratus overcast throughout. Here the diurnal range of soil heat flux is 6.3 ly/hr. Interestingly, the noon-time soil heat flux, instead of being maximum, has a negative value, 0.5 ly/hr, as a result of heavy showers at the time. After 15 LAT, soil heat flux becomes negative and the day's total is —11.7 ly.

In contrast to the monsoon season, the diurnal curves of soil heat flux in the post-monsoon and winter season exhibit a clearly defined maximum

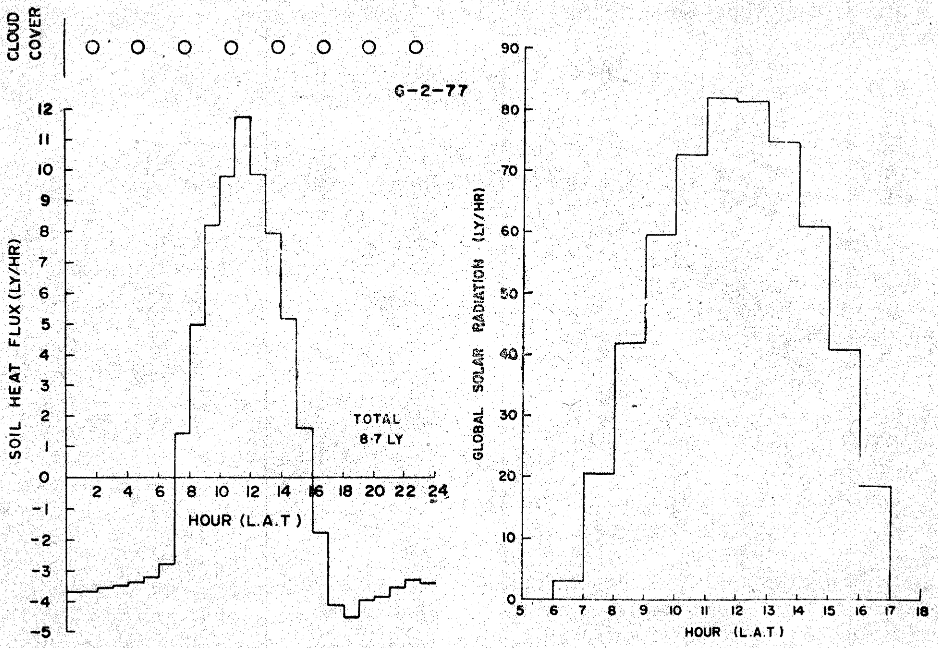

Fig. 6. Winter season

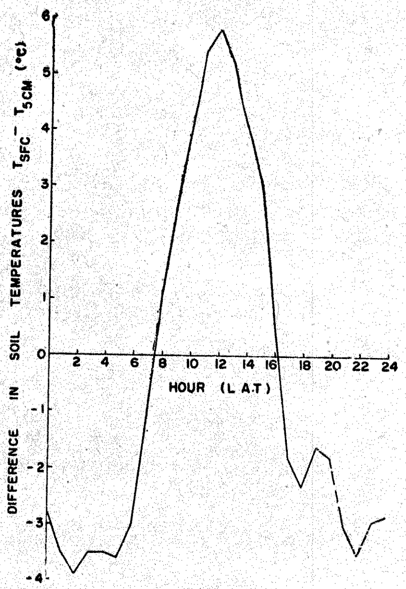

Fig. 7. October 1970

around local noon and have a regular and symmetrical shape. In the post-monsoon season (Figs. 3-4), the diurnal range of soil heat flux increases to four or five times the monsoon values. The daily total is positive and considerably high. These features are clearly attributable to the rise in incoming global solar radiation after the monsoon (Figs. 3-4) and the drying up of the soil at all depths (Table 1). Cloudiness, however, retains its dominant influence. During the night, clearer skies permit greater loss of heat from the soil to the atmosphere. On the other hand, less clouding during the day leads to a higher influx of heat into the soil. This explains the soil heat flux total dropping from a value of 98.4 ly on 11 October 1976 to 49.1 ly on 13 October which was cloudfree at night.

The two winter situations (Figs. 5-6) show that the maximum is less pronounced than in the post-monsoon, *viz.*, about 11 ly/hr. The negative values are consistently of the order of 3 to 5 ly/hr. Since both the days are marked by cloud-free skies, their soil heat flux patterns are nearly identical. Soil heat flux is seen to change its direction of flow at the same time as in other seasons in the morning, *i.e.*, 07 LAT, but earlier in the evening, *i.e.*, 16 LAT in association with the reduced length of day. The 24-hour sum is 7.1 and 8.7 ly respectively on the two winter days considered, suggesting that even in winter a small amount of heat does go into the soil.

4.2. *Thermal conductivity of soil*

For chemically pure substances, λ is a property of the substance and therefore a constant. In the case of soils, λ depends firstly on the soil type. For a given soil, it is a function of the water content and thus varies with place and time. An increase in soil wetness leads to an increase in λ.

According to the data presented by Van Wijk (1965), a clay soil devoid of all moisture has a thermal conductivity of 0.6 m cal / cm / sec /°C. For the same soil, the λ values for volumetric soil moisture content of 20 and 40 per cent are quoted as 2.8 and 3.8 m cal/cm/sec/°C respectively. These are several times higher than the value of λ for dry soil.

Although in the present study, λ was not specifically measured, the observations of soil heat flux in the monsoon season clearly point out the strong effect of precipitation on λ. In the monsoon, the diurnal range of soil temperature is limited, while λ is higher than in other seasons, with the result that the diurnal range of soil heat flux is grossly suppressed. The 24-hour total can even become negative with the overall flow of heat directed from the soil to the atmosphere.

4.3. *Estimation of soil heat flux from soil temperature*

Eqn. (2.2) can be used to estimate the soil heat flux if the soil temperature gradient and thermal conductivity are known. However, in order to compare the direct observations of soil heat flux presented in this paper with such estimates, it would have been necessary to continuously monitor the soil temperature at various depths and the thermal conductivity of the soil, which was not possible. Only an order of magnitude check was, therefore, attempted using hourly soil temperatures recorded in previous experiments at the Central Agrimet. Observatory, Pune.

The diurnal variation of the soil temperature difference between surface and 5 cm depth ($\triangle T = T_{SFC} - T_{5cm}$) for October 1970 is shown in Fig. 7. This is the mean of two series of observations made on 1-2 and 15-16 October 1970 using mercury-in-glass thermometers at the surface and 5 cm depth. Sky condition on 1-2 October 1970 was mainly cloudy with occasional light rain or drizzle. On the latter days, the sky was clear in the forenoon and cloudy in the afternoon.

The shape of the $\triangle T$ curves bears a close resemblance to the observed soil heat flux in October 1976 (Compare Figs. 4 and 7). Putting $\triangle z = 5$ cm in Eqn. (2.2) and assuming $\lambda = 10$ cal cm/hr/°C for post-monsoon conditions, following Van Wijk, the soil heat flux would range between 11.6 ly/hr at noon and —7.8 ly/hr at night. Considering the fact that conditions in October 1970 and 1976 were far from identical and that the value of λ could also be quite different from the assumed one, these values compare well with those of Fig. 4.

The high variability of λ presents particular problems in the indirect estimation of soil heat flux in the monsoon season. This is one of the reasons why most studies in the field are restricted to the nonmonsoon months (*e.g.,* Subrahmanyam and Ratnam 1970, Ramakrishna Rao *et al.* 1977, etc). The use of soil heat flux plates overcomes such difficulties.

5. Conclusions

(*i*) The seasonal variation of the soil heat flux is attributable to the annual cycle of global solar radiation and the progressive desiccation of soil moisture after the withdrawal of the monsoon. The diurnal variation of soil heat flux is influenced by cloudiness and precipitation.

(*ii*) The measurements in Pune black cotton soil show that for the period June-February, the highest daily flux into the soil is in the post-monsoon season. In winter also, a small amount of heat goes into the soil. The reverse flow takes place on rainy days in the monsoon season.

(*iii*) Soil heat flux plate measurements are shown to be compatible with indirect estimates. However, fluctuations in thermal conductivity of the soil can significantly alter the otherwise regular form of the diurnal variation of soil heat flux. Hence, computations of soil heat flux can have limited validity in the monsoon season unless the influence of soil water content is parameterised realistically. Here the flux plate can be employed with certain advantage.

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