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Energy balance at the land-surface interface

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सार — आई० आई० टी० एम०, पाषाण, पुणे में छोटे पैमाने पर एक क्षेत्रीय प्रयोग किया गया और अनाच्छादित मृदा पर मेघमय तथा मेघरहित दिनों के लिए भू-सतह के नीचे ऊर्जा बजट का अध्ययन किया गया। उपकरणयुक्त टॉवरों, एक नेट रेडियोमीटर तथा मृदा तापमान अन्वेषी का प्रयोग करते हुए ऊर्जा बजट के सभी घटकों, जैसे, संवेद्य ऊष्मा अभिवाह, पार्श्व ऊष्मा अभिवाह, मृदा ऊष्मा अभिवाह और नेट विकिरण को सीधे मापा गया तथा ऊर्जा संतुलन का आकलन किया गया। जब पूरे दिन के ऊर्जा बजट पर विचार किया गया तो इसे काफी संतुलित पाया गया। ऊर्जा बजट के एक भाग के रूप में बॉवन के अनुपात पर भी चर्चा की गई है।

ABSTRACT. A small scale field experiment was conducted at the Indian Institute of Tropical Meteorology (IITM), Pashan, Pune and the energy budget at the land surface interface was studied for clear and cloudy days over bare soil. Using instrumented towers, a net radiometer and soil temperature probe, all the components of the energy budget, *i.e.*, the sensible heat flux, latent heat flux, soil heat flux and net radiation were measured directly and the energy balance was computed. It is observed that when considered over the whole day, the energy budget is fairly balanced. As a part of energy budget, the Bowen's ratio is also discussed.

Key words — Sensible heat flux, Latent heat flux, Soil heat flux, Net radiation, Energy budget.

1. Introduction

It has been increasingly realised that land surface processes significantly influence weather and climate. Charney *et al.* (1977), Shukla and Mintz (1982), Sud and Smith (1985) have shown the need for inclusion of land surface exchange processes in the meteorological models. To parameterize land surface processes many field experiments on medium scale and large scale have been conducted. Amongst these, HAPEX-MOBILHY (Andre *et al.* 1986), FIFE (Sellers *et al.* 1988) and La Crau experiments are major ones. In these experiments, emphasis was given to observational techniques, and the various fluxes were determined precisely and validated with the help of satellite observations.

In some of the bigger programmes like World Climate Research Programme (WCRP) and Global Energy and Water Cycle Experiment (GEWEX), the measurement programmes are planned to resolve 'scaling-up' problems of smaller grid point observations to mesoscale grid point observations. That is to begin with, observations regarding partition of solar energy over a plain land and over a vegetated land, soil moisture and roughness, are taken on a small scale of 10×10 m or 100×100 m. The present study is a small scale experiment which may be the beginning of an experiment in the understanding of large grid mesh.

A small scale field programme was conducted at the Indian Institute of Tropical Meteorology (IITM), Pashan, Pune, (18° 32'N, 73° 51'E), to study the partition of energy at the land surface interface. Earlier studies on land surface energy balance have been reported by Mitsuta *et al.* (1973) and Smith *et al.* (1991). Mitsuta studied the partition of incoming energy over a period of 24 hours and tried to find out the imbalance. Smith's elaborate experiment consisted of the installation of net radiometer, sonic anemometer, soil thermometer, Bowen's ratio measuring instrument, flux plates etc. Using these infrastructures, Smith tried to verify the evapotranspiration equations given by Penman.

The aim of the present experiment is to study the partition of the incoming energy at the land surface interface using tower instrumentation, soil temperature probe and a net radiometer.

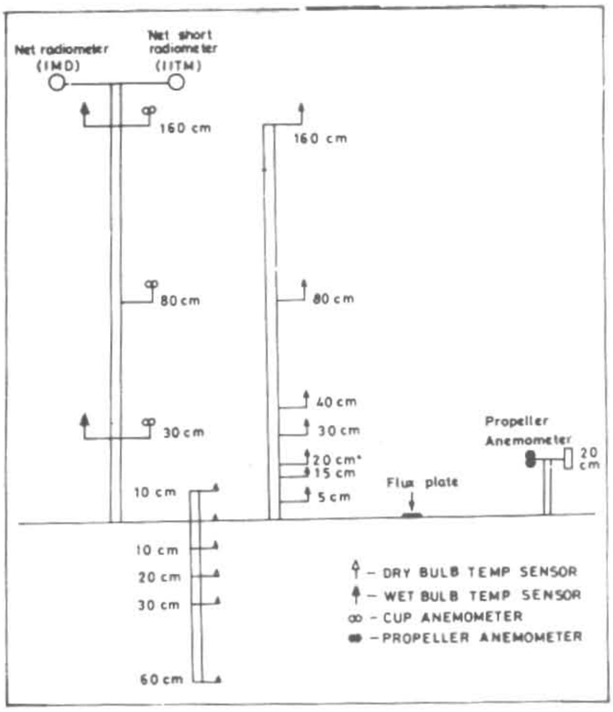


Fig. 1. Schematic diagram of different instrumented towers used during the experiment

2. Materials and method

2.1. *Experimental details*

2.1.1. *Observational site*

The experiment was conducted during 5-22 May 1992 at IITM, Pashan, Pune (18° 32′N, 73° 51′E, 559 m amsl). The observational site is flat, bare soil terrain surrounded by short, dry grass. The fetch to height ratio was more than 100.

2.1.2. *Instrumentation*

Fig. 1 shows the schematic layout of different towers and their instrumentation. A seven level temperature tower of height equal to 160 cm, consisted of three terminal linearised thermistor sensors (2 mm diameter) manufactured by M/s Yellow Springs Instrument Co., (YSI), USA, which were mounted at 5, 15, 20, 30, 40, 80 and 160 cm. Two 160 cm tall towers consisting of wind and temperature sensors (dry and wet) were erected. Anemometers were installed at heights of 30, 80 and 160 cm and wet bulb sensors were mounted at 30 and 160 cm height. Three terminal linearized YSI thermistors (2 mm diameter) were used as wet bulb sensors with wetting arrangement provided with a muslin cloth and distilled water source available in a small plastic bottle. All the thermistors installed here and on the other towers were operated in resistance mode. Another probe to measure soil temperature at the surface, 10 cm above the soil surface and 10, 20, 30 and 60 cm respectively, below the surface was also installed nearby. In this probe, four terminal linearized YSI thermistors (3.16 mm diameter) were utilized. In this system also, the thermistors were operated in resistance mode (Pillai *et al.* 1993).

A net radiation measuring radiometer supplied by India Meteorological Department (IMD) was deployed on the first tower (160 cm height) for obtaining the net radiation, Q_N. Its spectral range is from 0.29 to 50 μm and a direct output voltage is obtained with 1 mV corresponding to 35.64 W m^{-2}. For computing the net short wave radiation R (S), two pyranometers manufactured by M/s LICOR Inc., USA, with spectral range 0.4-1.1μm were mounted back-to-back on the same tower adjacent to the net radiometer. Thus, the radiometer facing upwards records the shortwave radiation, whereas the radiometer facing the surface estimates the reflected short wave radiation. Their sum gives the net short wave radiation. These radiometers have an ouput of 100 W m^{-2} per 1 mV. The outputs of these three radiometers are recorded on an analog 6-channel Yokogawa strip chart recorder. The data is read with a resolution of 0.2 mV for the net radiometer and 0.1 mV for the pyranometers.

A flux plate was also installed to directly determine the heat flowing into the soil. The flux plate, manufactured by M/s International Thermal Instruments Co., USA, has 2″ × 2″ dimension with thermocouples sandwiched between polymide glass plates. The flux plate, when in contact with the soil, produces a signal directly proportional to the heat flux flowing into the soil or coming out of the soil depending upon the temperature difference at the land surface interface. An output of 1 millivolt corresponds to 25.74 W m^{-2}. To monitor the variation of the surface heat flux with surface wind, a propeller anemometer with vane attachment was installed near the flux plate at a height of 20 cm from the soil surface.

2.1.3. *Data recording*

Fig. 2 shows the data acquisition set up for the experiment. Slow data from the soil temperature sensor, flux plate and net radiometer were recorded continuously on an analog strip chart recorder. Fast data acquired from dry bulb,wet bulb thermometers and anemometers were fed through a commercially available 12 channel data logger and recorded on floppies through a PC.

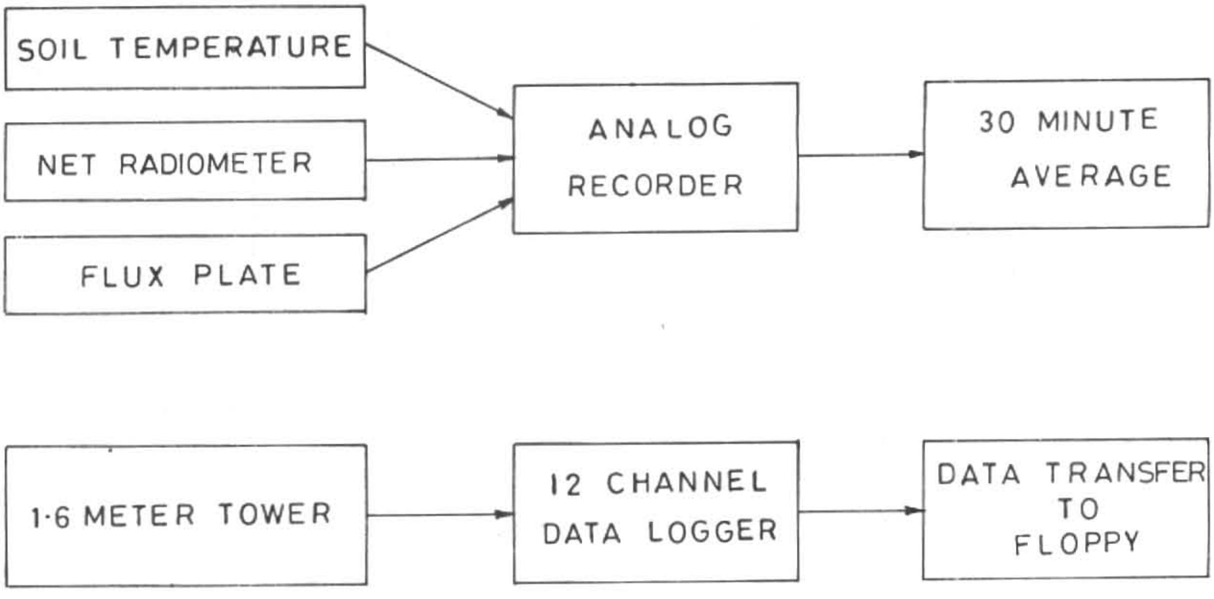


Fig. 2. Data acquisition set-up for different instruments

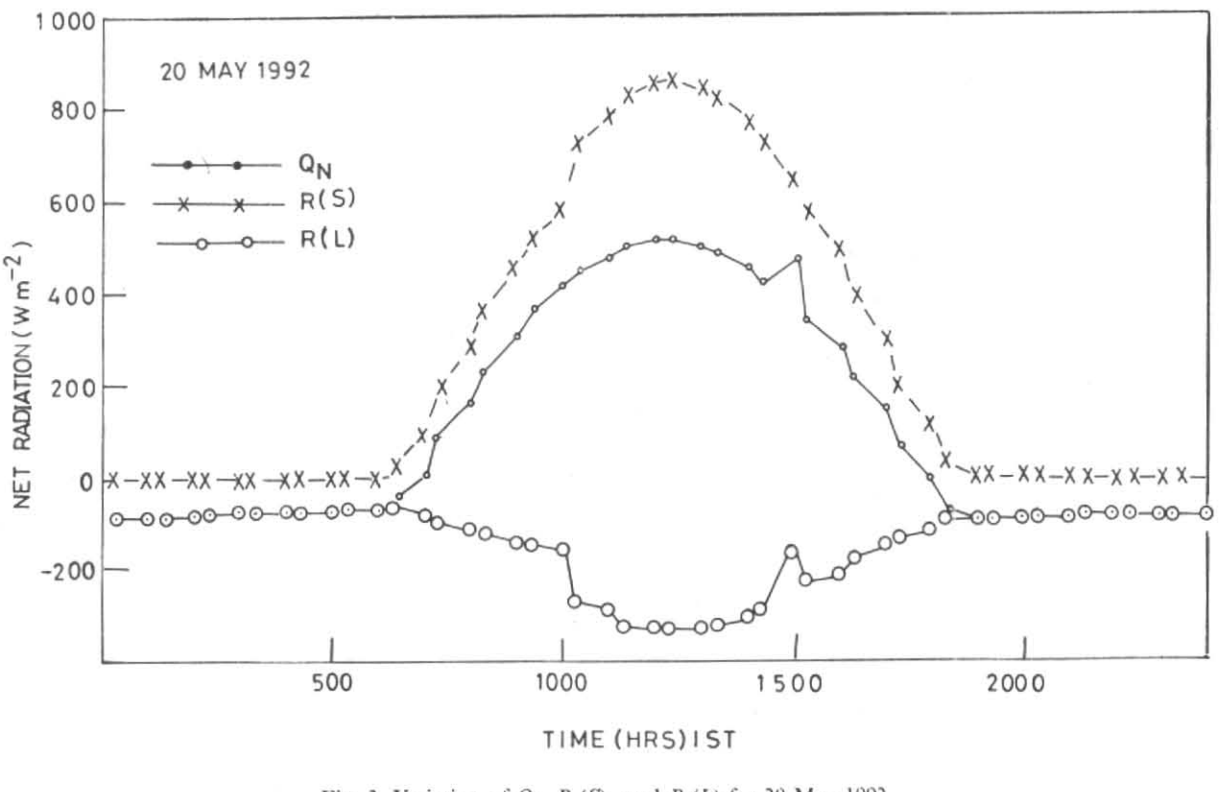


Fig. 3. Variation of Q_N, R (S) and R (L) for 20 May 1992

Data from the 160 cm high towers were recorded for a duration of 20 minutes every hour. The sampling was done at a rate of one sample every five seconds.

2.2. *Net radiation*

The net radiation (Q_N) was measured by the net radiometer at a height of 160 cm on the tower. The

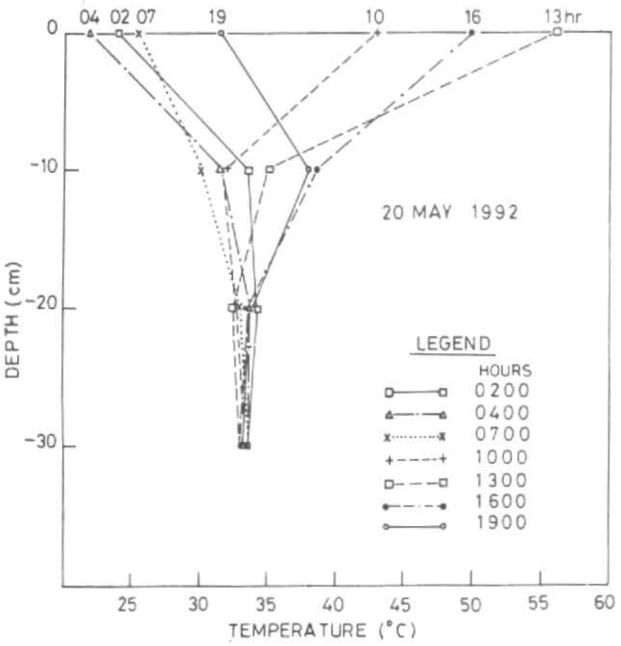


Fig. 4. Soil temperature profile for 20 May 1992

net radiation received at the surface is the sum of net shortwave radiation R (S) and net long wave radiation R (L). Q_N is directly read from the output of radiometer supplied by IMD, whereas R (S), the net shortwave radiation is recorded by the LICOR sensor. The difference between these outputs, *i.e.*, $[Q_N - R(S)]$ gives the net long wave radiation R (L). Fig. 3 shows the variation of Q_N, R (S) and $R(L)$ on the day, 20 May 1992. The positive values indicate incoming radiation towards the earth's surface, whereas the negative values indicate radiation going away from the earth's surface. As observed normally, during the daytime the net shortwave gain by the earth's surface is more than the net long-wave loss. At night, as there is no incident shortwave radiation the net radiation is equal to the net long wave radiation loss from the surface.

2.3. *Soil temperature*

Fig. 4 shows the soil temperature profile upto a depth of 30 cm, on 20 May 1992, which conform to the temperature profiles usually observed (Oke 1987, Rosenberg *et al.* 1983). During the daytime, the rate at which solar energy is incident is more than the rate of dissipation. As a result, the accumulated heat causes the surface temperature to rise. The pattern of diurnal variation of temperature recorded at the surface is followed in the lower layers with an exponential decrease in amplitude. There is also a lag in the time at which the maximum temperature is recorded in the successive layers when compared to surface maxima and this lag increases with depth.

The soil surface temperature has a daily variation of 25°-30°C. The amplitude of this swing decreases with depth, attaining a value of around 1°C only at a depth of 30 cm.

2.4. *Energy budget equation*

For deriving a simplified equation for the energy budget near the surface, the interfacial layer is assumed to be having a finite depth which again includes small scale surface inhomogenities. This layer must have finite mass and heat capacity which would allow the energy to be stored in or released from the layer over the given time interval. In the case of vegetated surface, the energy budget of the whole canopy layer has to be considered.

The simplified one dimensional energy budget for the thin land surface layer will be,

$$Q_N = Q_H + Q_E + Q_G \tag{1}$$

where, Q_N is the net incoming radiation. Q_H and Q_E are the sensible and latent heat fluxes to or from the air and Q_G the ground heat flux to or from the submedium.

The energy balance for the land surface interface is given by,

$$Q_N - (Q_H + Q_E + Q_G) = 0 \tag{2}$$

2.5. *Computation of fluxes*

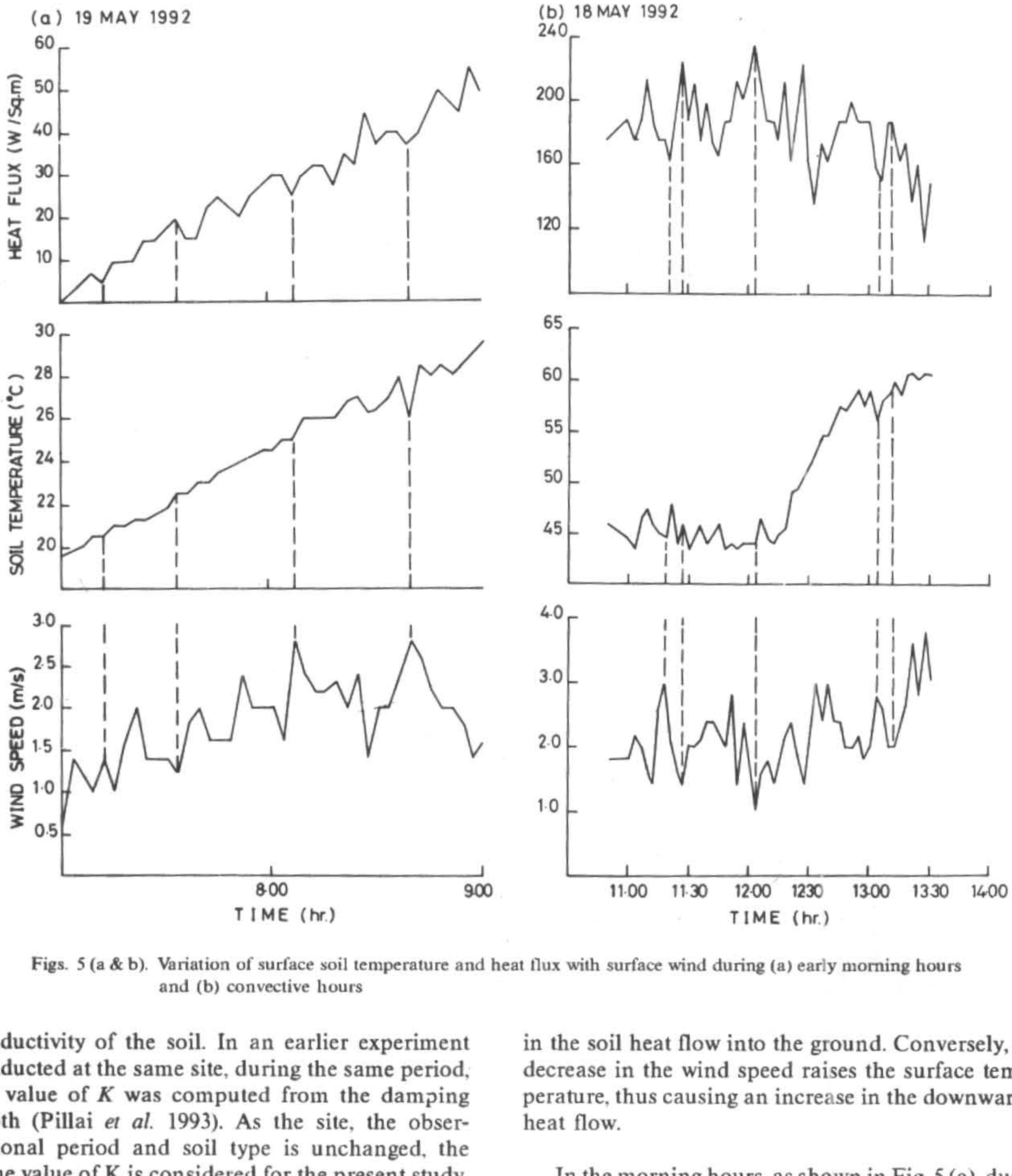
To study the energy balance at the interface of land surface, it is essential to determine the sensible heat flux Q_H, moisture heat flux Q_E and the ground heat flux Q_G. Evaluation of these fluxes is discussed below.

2.5.1. *Soil heat flux* (Q_G)

The soil heat flux (Q_G) can be evaluated from known temperatures at two depths below the soil surface. Considering temperatures at two levels, surface and 10 cm below the surface and assuming soil as a homogeneous medium, the soil heat flux is given by (Van Wijk 1965, Fritschen and Gay 1979) :

$$Q_G = -K \, dT / dz \tag{3}$$

where, dT/dz is the temperature gradient between surface and 10 cm level and K is the thermal



Figs. 5 (a & b). Variation of surface soil temperature and heat flux with surface wind during (a) early morning hours and (b) convective hours

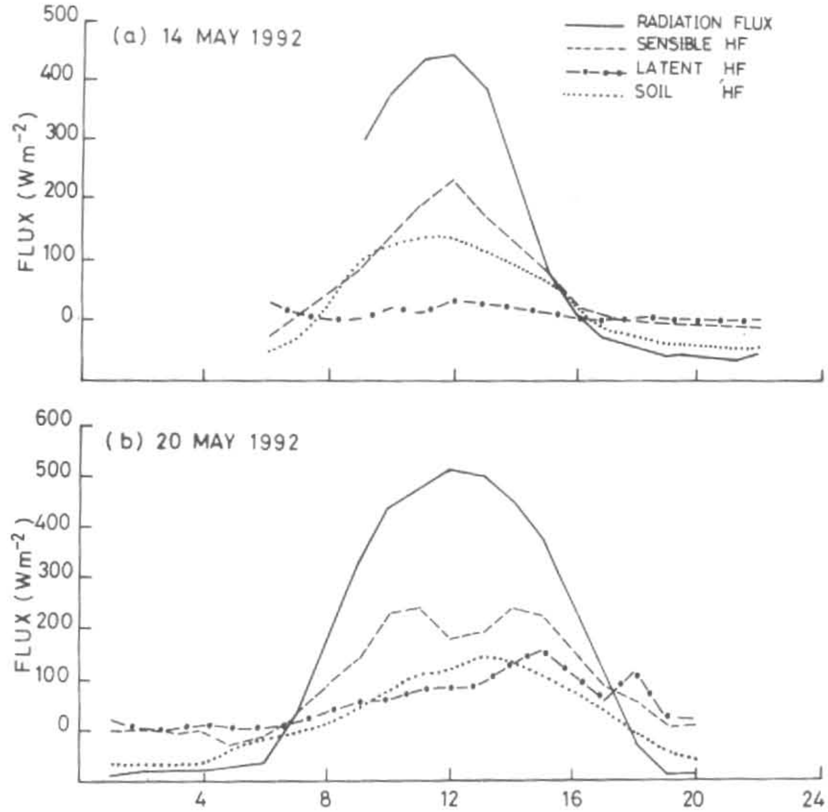
conductivity of the soil. In an earlier experiment conducted at the same site, during the same period, the value of K was computed from the damping depth (Pillai *et al.* 1993). As the site, the observational period and soil type is unchanged, the same value of K is considered for the present study, *ie.,* 7.12×10^{-1} W m^{-1} K^{-1}

The soil flux is a highly varying parameter which depends on many external parameters including wind and temperature. Fig. 5 (b) shows the variation of surface soil temperature and heat flux with the surface wind (horizontal), for 18 May 1992 between 1000-1400 hr. It is observed that for an increase in the surface wind there is a fall in the surface temperature which in turn causes a reduction in the soil heat flow into the ground. Conversely, a decrease in the wind speed raises the surface temperature, thus causing an increase in the downward heat flow.

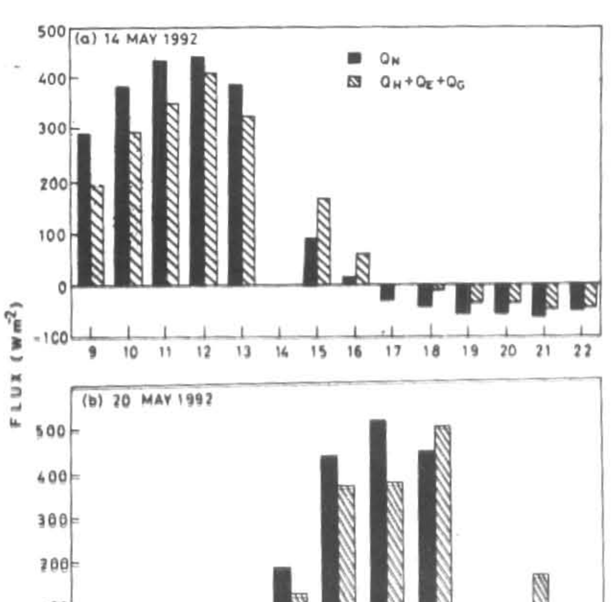
In the morning hours, as shown in Fig. 5 (a), during the period 0700-0900 hr, on 19 May 1992, though the surface temperature is continuously increasing, the same transient effect of surface wind is again reflected in the surface temperature and the soil heat flux.

2.5.2. *Sensible and latent heat fluxes* (Q_H & Q_E)

Using wet and dry temperatures and wind speed data at 30 and 160 cm, the sensible heat flux and



Figs. 6 (a & b). Variation of solar radiation flux, sensible heat flux, latent heat flux and soil heat flux for (a) 14 May 1992 and (b) 20 May 1992



Figs. 7 (a & b). Histogram of Q_N and $(Q_H + Q_E + Q_G)$

latent heat flux are evaluated by the profile technique (Oke 1987). Under neutral conditions, the flux profile equations are :

Sensible heat flux

$$Q_H = -\rho C_p k^2 z^2 \frac{(\Delta u \, . \, \Delta T)}{(\Delta z \;\; \Delta z)} \tag{4}$$

Latent heat flux

$$Q_E = -\rho L_v k^2 z^2 \frac{(\Delta u \, . \, \Delta q)}{(\Delta z \;\; \Delta z)} \tag{5}$$

where, ρ is the air density, C_p is the specific heat of air at constant pressure, L_v is the latent heat of evaporation, k is the Von Karman constant and z is the height. Terms in parenthesis are the respective gradient terms.

For evaluating the fluxes under non-neutral conditions, the equations are modified using dimensionless stability factors dictated by the similarity theory. The stability factor to be multiplied is $(\phi_M \, \phi_x)^{-1}$, where, $\phi_x = \phi_q$ or ϕ_H

TABLE 1

Partition of energy and energy balance on 20 May 1992

Time	Q_N	Q_H	Q_E	Q_G	B
0100	−84.00	0.00	19.49	−66.50	−36.99
0200	−77.00	−2.41	0.34	−70.00	−4.93
0300	−77.00	−5.18	1.65	−66.50	−6.97
0400	−77.00	−4.15	8.05	−66.50	−14.40
0500	−70.00	−32.10	2.88	−66.00	25.22
0600	−63.00	−15.34	1.81	−66.00	16.53
0700	28.00	19.23	6.77	−31.50	33.50
0800	182.00	85.06	30.56	7.00	59.38
0900	322.00	134.63	58.72	−45.50	83.15
1000	434.00	227.77	59.28	78.75	68.20
1100	476.00	236.75	77.19	112.00	50.06
1200	511.00	175.87	80.94	115.50	138.69
1300	497.00	188.84	82.37	147.00	78.79
1400	441.00	237.61	123.60	136.50	−56.71
1500	364.00	219.11	154.40	108.50	−118.01
1700	112.00	80.99	56.00	38.50	−63.49
1800	−28.00	51.16	111.40	−7.00	−183.56
1900	−91.00	4.78	19.58	−45.50	−69.86
2000	−91.00	5.30	18.81	−56.00	−59.11
Total	2709.00	1607.92	913.84	247.75	

Balance = 2709.00 − (1607.92 + 913.84 + 247.75)

= −60.51 W/sqm

Q_N = Net radiation (W/sqm)

Q_H = Sensible heat flux (W/sqm)

Q_E = Latent heat flux (W/sqm)

Q_G = Soil heat flux (W/sqm)

$B = Q_N - (Q_H + Q_E + Q_G)$ W/sqm

where, ϕ_M − dimensionless stability factor for momentum flux

ϕ_q − dimensionless stability factor for moisture flux

ϕ_H − dimensionless stability factor for sensible heat flux

TABLE 2

Partition of energy and energy balance on 14 May 1992

Time	Q_N	Q_H	Q_E	Q_G	B
0900	294.00	87.33	4.56	101.50	100.61
1000	385.00	144.09	24.90	127.95	88.06
1100	434.00	194.25	15.06	141.75	82.94
1200	441.00	233.91	35.52	140.00	31.57
1300	385.00	175.85	33.82	119.00	56.33
1500	91.00	83.40	17.95	70.00	−80.35
1600	14.00	26.93	6.13	28.00	−47.06
1700	−28.00	7.61	0.94	−10.50	−26.05
1800	−42.00	4.78	12.31	−28.00	−31.09
1900	−56.00	0.00	1.43	−35.00	−22.43
2000	−56.00	−2.96	4.59	−38.50	−19.13
2100	−63.00	−7.88	1.52	−43.75	−12.89
2200	−49.00	−8.99	5.51	−42.00	−3.52
Total	1750.00	938.32	164.24	449.95	

Balance = 1750.00 − (938.32 + 164.24 + 449.95)

= 197.49 W/sqm

Q_N, Q_H, Q_E, Q_G and B are the same as in Table 1.

With the substitution of ϕ_M and ϕ_x, Eqns. (4) & (5) are transformed to,

$$Q_H = -\,\rho C_p k^2 z^2 \frac{(\Delta u \, . \, \Delta T)}{(\Delta z \quad \Delta z)} (\phi_M \, \phi_H)^{-1} \tag{6}$$

$$Q_E = -\,\rho L_v k^2 z^2 \frac{(\Delta u \, . \, \Delta q)}{(\Delta z \quad \Delta z)} (\phi_M \, \phi_q)^{-1} \tag{7}$$

The empirical relations for different stabilities are (Dyer 1974, Oke 1987):

For stable conditions:

$$(\phi_M \, \phi_H)^{-1} = (\phi_M \, \phi_q)^{-1} = (1 - 5\, Ri)^2 \tag{8}$$

For unstable conditions:

$$(\phi_M \, \phi_H)^{-1} = (\phi_M \, \phi_q)^{-1} = (1 - 16\, Ri)^{3/4} \tag{9}$$

where,

Ri is the Richardson number being equal to,

$$\frac{g}{T} \, \frac{\partial T / \partial z}{(\partial u / \partial z)^2}$$

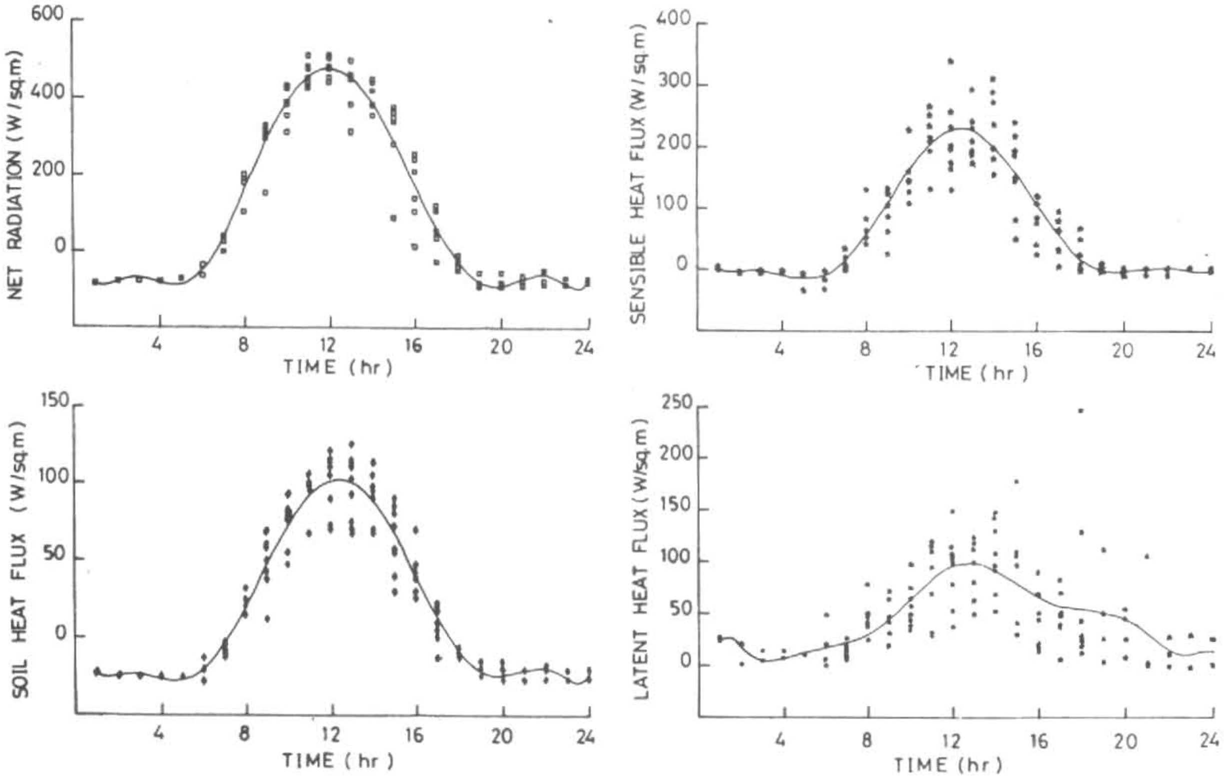


Fig. 8. Variation and the mean of the net radiation, sensible, latent and soil heat fluxes for the duration of the experiment

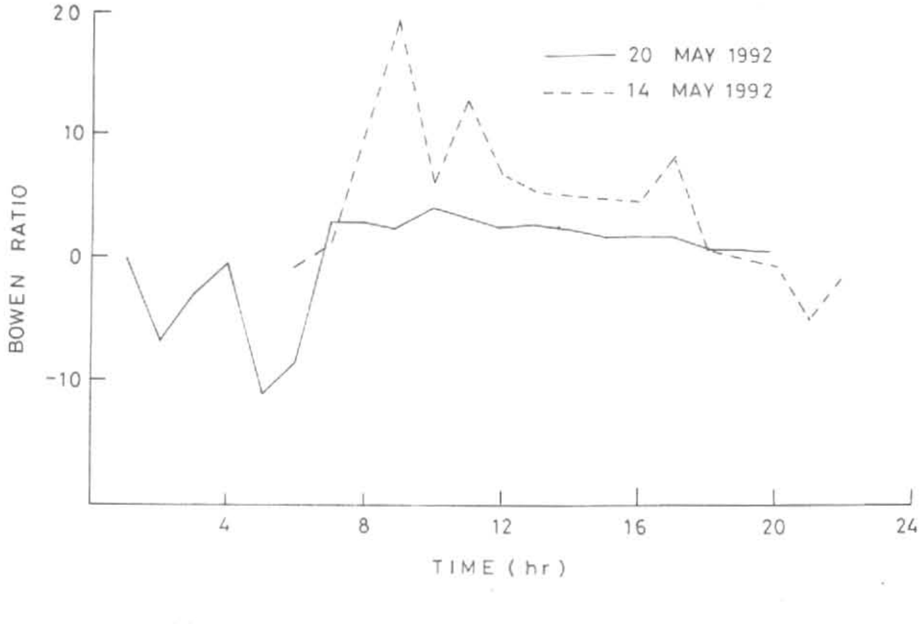


Fig. 9. Variation of Bowen's ratio for 14 and 20 May 1992

3. Results and discussion

As given above, the estimates of Q_H, Q_E and Q_G were made for all days commencing from 5 to 22 May 1992. As far as synoptic conditions are concerned the period between 16-22 May 1992 was clear with no clouds, whereas the period between 5-15 May was cloudy with 5-6 octa clouds all through the day. As mentioned earlier, data were collected every hour for 20 minutes' duration. Days on which maximum data were collected, *i.e.*, 20 May (during clear sky conditions − 19 hours data) and 14 May (during cloudy conditions − 14 hours data) are chosen for presentation here. Figs. 6 (a & b) show the variation of (1) solar radiation flux, (2) sensible heat flux, (3) latent heat flux and (4) soil flux estimated for 14 and 20 May 1992. Tables 1 and 2 show the balance of radiation, *i.e.*, residue between net radiation and other radiations for both days, *i.e.*, 20 and 14 May 1992. On 20 May 1992, Q_N is negative from 0100 to 0600 hr and from 1800 to 2000 hr, *i.e.*, the radiation is going away from the earth's surface. Similarly, Q_G is also negative, *i.e.*, the heat is flowing away from the earth's surface. Similar trend is observed on 14 May 1992, where Q_N and Q_G are negative from 1700 to 2200 hr. The imbalance over 20 hours for 20 May 1992 is 60.51 Wm^{-2} and that observed on 14 May 1992 is 197.49 Wm^{-2} for limited observation of 14 hours' period. The imbalance could be because of the other losses in the land surface energy exchange which are difficult to identify. Instrumentation errors of the order of ± 10% may also be present. Fig. 7 shows a histogram of Q_N and $(Q_H + Q_E + Q_G)$ for 14 and 20 May 1992. On the whole, Q_N is higher, further indicating that there are unaccounted losses at the land-surface interface. Fig. 8 shows the variation and the mean of the net radiation and the different fluxes observed for the duration of the experiment.

3.1. *Bowen's ratio*

The Bowen ratio is also estimated which provides a simple expression for evaporation in terms of sensible heat flux, mean temperature and specific humidity measurements in the surface layer.

Bowen's ratio (β) is defined as the ratio of sensible heat flux to latent heat flux,

$$\beta = Q_H / Q_E = \frac{C_p \, dT/dz}{L_v \, dq/dz} \tag{10}$$

where, q is specific humidity, T is the temperature, C_p is specific heat at constant pressure and L_v is the latent heat of evaporation.

Over a dry grass land this ratio is 0.8. The ratio is between 2 to 6 for semiarid areas. The experimental site may be treated as a dry place because in the month of May at Pune, there is very less humidity. This ratio was evaluated for 14 and 20 May 1992 and is shown in Fig. 9. The solid line indicates β for 20 May 1992, whereas the broken curve for 14 May 1992. On 20 May 1992, β was negative in the early morning hours which may be true because the sensible heat flux is negative during this period. From 0800 hr onwards β is between 2 and 3 and this state continues upto 2000 hr. On 14 May 1992 the situation is entirely different and the β value fluctuates probably due to cloudiness and reaches a value of 19 around 0800 hr and later, around noon, it stabilizes between 5 and 6 and a small kink is also observed around 1700 hr.

4. Conclusion

A small scale field experiment was conducted to evaluate the partition of energy at the land surface interface. An instrumented tower, a soil temperature probe and a net radiometer were installed at the site and hourly observations of 20 minutes' duration were recorded. From the experiment, the net radiation is measured and the surface sensible, latent and soil heat fluxes are estimated by the profile technique. It is observed that the energy is fairly balanced. Bowen's ratio shows marked variations on cloudy days. Such studies of the land surface exchange processes, the fluxes at the interface and the partition of energy are important in understanding the local weather which in turn influences the meso-scale atmospheric processes.

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