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# Characteristics of radiative and non-radiative energy fluxes over monsoon trough zone

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**सार** — इस शोध-पत्र में धरातली सतह में विकिरणी और अविकरणी ऊर्जा फ्लाक्सों की क्रियाविधि को बताने के लिए घंटेवार विश्वस्तरीय विकिरण MONTBLEX-1990 के धीमी प्रतिक्रिया से संबंधित आँकड़ों का और जुलाई 1990 में वर्षा और बिना वर्षा वाले दिनों के दौरान वाराणसी और जोधपुर में धरातली प्रेक्षण का उपयोग करते हुए नेट विकिरण का आकलन, संवेघ, गुप्त और मृदा ऊष्मा फ्लक्स का अध्ययन किया गया है। एक विमीय ऊष्मा चालन समीकरण का हल निकालते हुए धरातल के दैनिक और घंटेवार तापमान का आकलन किया गया है तथा प्रतिवलन पुनः स्थापित पद्धति का उपयोग करते हुए मृदा ऊष्मा फ्लक्स का आकलन किया गया है। विकिरण के स्टीफेन बेल्टज़मान नियम द्वारा संवहनी क्षेत्र में बृहत्तम दैनिक विभिन्नताएँ पाई गई हैं। इनसे प्राप्त हुए परिणामों से यह पता चला है कि सामान्यतः मेधमयी दिन में जोधपुर में धरातल से ओ.एल. आर. 473.0-537.6 $Wm^{-2}$ ओर वाराणसी में 497.4-548.4 $Wm^{-2}$ की परिधि में पाए गए हैं। सापेक्षिक आर्द्रता और मेघमयता में वृद्धि के साथ ओ.एल.आर. में आई कमी में 10% की वृद्धि पाई गई है। मेघमयता वाले दिनों में बृहत्तम अधोमुखी मृदा ऊष्मा फलक्स के दैनिक माध्य वाराणसी और जोधपुर में क्रमशः 206.4 और 269.4 $Wm^{-2}$ पाए गए हैं। वाराणसी और जोधपुर में नेट विकिरण का लगभग 40-50% भाग मृदा ऊष्मा फ्लक्स में चला जाता है। इस प्रकार से घंटेवार अविकिरण ऊर्जा फ्लक्सों का सार नेट विकिरण के बराबर नहीं पाया गया है। जबकि बिना वर्षा वाले दिन के समय फ्लक्सों के दैनिक संचयी मान नेट विकिरण के बराबर पाए गए हैं।

**ABSTRACT.** In order to describe behaviour of radiative and non-radiative erergy fluxes in the surface layer, computation of net radiation, sensible, latent and heat soil flux has been done using hourly global radiation, slow response data of MONTBLEX-90 and surface observation of Varanasi and Jodhpur during rainy and non-rainy days in July 1990. Daily and hourly ground temperature is calculated solving one dimensional heat conduction equation and soil heat flux is computed using force restored method . Outgoing Longwave Radiation (OLR) is calculated by Stefan-Boltzmann law of radiation and the largest diurnal variability was found over dry convective zone. Results show that OLR from the ground lies in the range 473.0-537.6 $Wm^{-2}$ at Jodhpur and 497.4 - 548.4 $Wm^{-2}$ at Varanasi during generally cloudy day. The dip in OLR is increased by 10% with increase of relative humidity and cloudiness. Daily mean of the largest downward soil heat flux are found as 206.4 and 269.4 $Wm^{-2}$ at Varanasi and Jodhpur respectively during cloudy day. About 40-50% of net radiation is imparted to soil heat flux at Varanasi and Jodhpur. Sum of the hourly non- radiative energy fluxes has not been balanced by net radiation while daily cumulative value of the fluxes balances the net radiation during non-rainy day.

**Key words** – Sensible, Latent and soil heat flux, Radiative, Non-radiative, Net radiation, Outgoing longwave radiation, Ground temperature.

## 1. Introduction

It is well known that land surface processes play a dominant role to activate weather in the tropical region. Recently several field experiments were conducted in order to find out relationship between surface layer physical processes and weather phenomena (Andre *et al.*, 1986, Saxena *et al.* 1996). Coupling between soil surface interface and atmosphere is established by upward transfer of sensible heat and moisture flux. Since these physical processes occur on the ground, consequently the associated inherent mechanism depends on the physical state of soil and prevailing meteorological conditions. Transformation of net radiation into non-radiative energy fluxes is a complex problem because variation of incident global radiation, cloudiness, soil wetness and surface albedo in space and time. The surface physical characteristic provides sufficient feedback mechanism for regulating weather system in the atmosphere and magnitude of the fluxes determine soil wetness (Delworth and Manabe, 1989).

TABLE 1

**Cloud cover and duration of rain**

| Date | Time (IST) | Varansi | | | Jodhpur | | |
|---|---|---|---|---|---|---|---|
| | | Cloud type | Cloud amount (Octa) | Duration of rain (IST) | Cloud type | Cloud amount (Octa) | Duration of rain (IST) |
| 1 July '90 | 0830 | Sc, Cu, Ac | 8 | 0830-0920 | | | |
| | 1730 | Cu, Ac | 5 | | | | |
| 2 July '90 | 0830 | | | | Sc, As | 7 | 2105-2135 |
| | 1730 | | | | Sc, Cu, As | 6 | |
| 3 July '90 | 0830 | Sc, Cu, Cb, Ac | 7 | 1420-1940 | St, Ac, As | 8 | 0145-1938 |
| | 1730 | Sc, Ac | 6 | | St, Ac, As | 8 | |
| 9 July '90 | 0830 | | | | St, Sc, Ac | 7 | No Rain |
| | 1730 | | | | St, Ac | 5 | |
| 11 July '90 | 0830 | | | | Sc, As | 8 | No Rain |
| | 1730 | | | | Sc, As | 7 | |
| 12 July '90 | 0830 | Sc, Ac | 8 | 0115-1440 | Sc, Ci | 6 | 0030-0040 |
| | 1730 | Sc, Cb, Ac | 7 | | Sc, Ci | 5 | |
| 21 July '90 | 0830 | Sc, Ac | 7 | 1620-1705 | Sc, Cu | 6 | No Rain |
| | 1730 | Sc, Cu, Cb | 7 | | Sc, Ci | 6 | |
| 24 July '90 | 0830 | St, Cu | 5 | 2200-2240 | Ac | 4 | No Rain |
| | 1730 | Cu, Ci | 5 | | Sc, Ac | 7 | |

Note : St-Stratus, Sc-Stratocumulus, Cu-Cumulus, Cb-Cumulonimbus, Ac-Altocumulus, As-Altostratus and Ci-Cirrus

Diurnal forcing of net radiation is an outstanding feature which provides a good approximation to evaluate the non-radiative energy fluxes. The radiative energy is balanced by the energy flux in surface layer which are most sensitive to ground wetness . Thus, the net radiation is required to be dealt with its partitioning into non-radiative fluxes as they act as one of the forcings of micrometeorological atmospheric variability (Delworth and Manabe, 1988). The objective of the papers is to study quality and quantity of radiative and non-radiative fluxes during rainy and non-rainy days at Varanasi and Jodhpur. Reckoning the energy fluxes, it is also attempted to investigate whether the diurnal cycle of sensible, latent, soil heat as well as outgoing longwave radiation exists as an energy source in dry and moist convective zone.

## 2. Data and weather system

MONTBLEX-90 slow response data of Varanasi and Jodhpur for the month of July 1990 are used. These data set were recorded at a frequency of 1Hz at both the stations by means of PC based telemetry system in the data logger. Chief soil surface layer peremeters are : soil and air temperature, windspeed and relative humidity. Soil temperature observation was taken at 0.1, 0.2 and 0.3 m depth below the ground. Air temperature, windspeed and relative humidity are considered only at 1,15 and 30 m height above the ground. Only those days are considered whereon continuous record of weather elements is available (Table 1). Hourly value of global radiation and surface observation are utilized in respect of those days for which MONTBLEX-90 tower data is available. Duration of rain, prevailing cloud amount and mean sea level pressure have been taken from meteorological register of the station. Slow response tower data have been archived at one minute interval round the clock (0000-2400), therefore the data are scrutinized for each weather element and hourly mean has been computed. Finally dataset consisting of hourly mean of soil and air temperature, relative humidity, windspeed and global raidation for 2,3,9,11,12,21 and 24 July 1990 of Jodhpur and 1,3,12,21 and 24 July 1990 of Varanasi are made to compute radiative and non-radiative fluxes.

There was rain under the influence of low pressure system and associated upper air circulation during 1-8 July 1990 at both the stations. During the period monsoon was active to vigrous in Uttar Pradesh and Rajasthan. Generally cloudy sky without rain was observed during remaining days of July 1990 at Jodhpur while rain was reported on most of the days at Varanasi.

## 3. Methodology

Radiant heat exchange is ascertained by net radiation which is equal to the difference between incoming and the outgoing radiation. Hourly value of global radiation is used to determine net radiation which is the sum of the absorbed fractions of the incoming solar radiation and atmospheric infrared radiation and reduced by outgoing long wave radiation from the ground. Based on land surface studies by Sellers and Dorman (1987), Viterbo and Beljaars (1995) and Garratt (1992), net radiation can be expressed as :-

$$R_n = R(1-\alpha)+R_a - \in \sigma T_g^4 \quad (1)$$

$$R_a = 5.41\ T_a - 1285 \quad (2)$$

Where, $R_n$ = Net radiation ( $Wm^{-2}$ ),

$R_s$ = Global radiation ($Wm^{-2}$ ),

$R_a$ = Downward infrared radiation ($Wm^{-2}$ ),

$\alpha$ = Albedo (0.15),

$\in$ = Emissivity of the soil (0.996),

$\sigma$ = Stefan Boltzmann constants ($5.67\times10^{-8} Wm^{-2}K^{-4}$),

$T_g$ = Hourly average ground temperature and

$T_a$ = Hourly average air temperature at 1 m height.

Daily mean value of soil temperature at 0.1, 0.2 and 0.3 m depth are computed. Since, the mean soil temperature varies linearly with depth, one can extrapolate the daily mean of ground temperature (Rao 1995). One dimensional heat conduction equation is solved to derive thermal diffusivity of soil as :

$$\frac{\partial T}{\partial t} = D\,\frac{\partial^2 T}{\partial^2 Z} \quad (3)$$

Where, $D$ = Thermal diffusivity of soil, differentiation of soil temperature with respect to time is determined using hourly value of soil temperature at 0.1 m depth and double differentiation of temperature with respect to depth is obtained by central differencing scheme using hourly temperature at 0.1,0.2 and 0.3 m depth. Hourly ground temperature is computed by the following solution of the equation.

$$T_s(0,t) = \overline{T} + \overline{T}_{\text{amp}} \sin\left(\omega t - \frac{\pi}{2}\right) \quad (4)$$

Where, $\overline{T}$ = Daily mean ground temperature,

$\overline{T}_{\text{amp}}$ = Amplitude of ground temperature and

$\omega$ = Angular frequency of diurnal oscillation.

Finding amplitude at 0.1 m depth, ground temperature amplitude is determined using following relation as :

$$\overline{T}_{\text{amp}} = T_{\text{amp}} \in^{\beta Z} \quad (5)$$

Where $T_{\text{amp}}$ = Amplitude at 0.1 m depth

$$= \frac{T_{\max} - T_{\min}}{2},$$

$z = 0.1$ m and $\beta = \sqrt{\omega / 2D}$

Utilizing hourly global radiation and ground temperature, net radiation is computed from Eqn. 1. Assuming only vertical transport of fluxes one can express net radiation in terms of non-radiative fluxes as :

$$R_n = SH + LE + GH \quad (6)$$

$$SH = -\rho C_p\, u_* \theta_* \quad (7)$$

$$LE = -\rho\, u_* q_* \quad (8)$$

Where, $\rho$ = Air density,

$C_p$ = Specific heat at constant pressure,

$u_*$ = Frictional velocity,

$\theta_*$ = Scaling temperature,

$q_*$ = Scaling specific humidity,

SH = Sensible heat,

LE = Latent heat and

GH = Soil heat flux.

Monin obukhov similarity theory has been used to derive sensible and latent heat flux. All computational operations are executed as adopted in profile technique (Jha and Sinha Ray, 1995, Bergstrom, 1986 and Mohanty *et al.*, 1992). Hourly air temperature, windspeed and relative humidity pertaining to 1, 15 and 30 m height of MONTBLEX tower are utilized to compute scaling parameters, *viz*; frictional velocity, temperature and

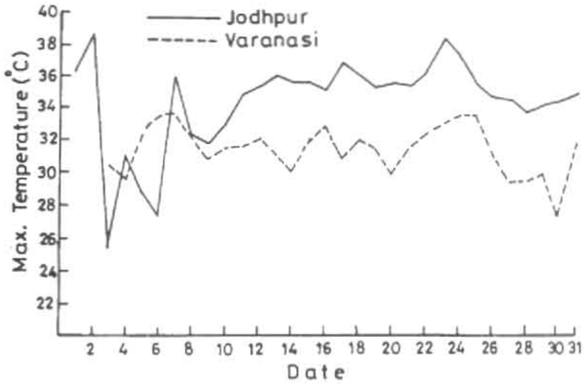



Fig. 1. Daily variation of maximum temperature during July 1990

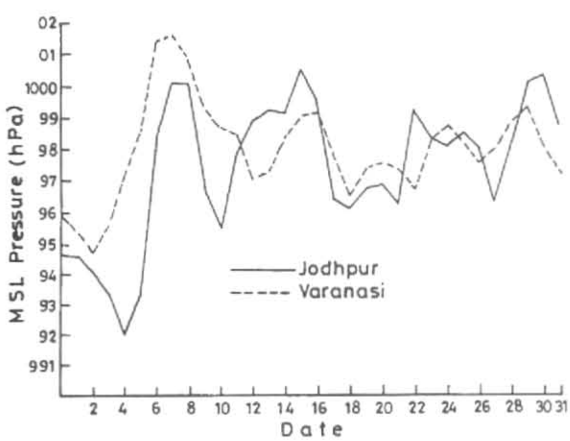
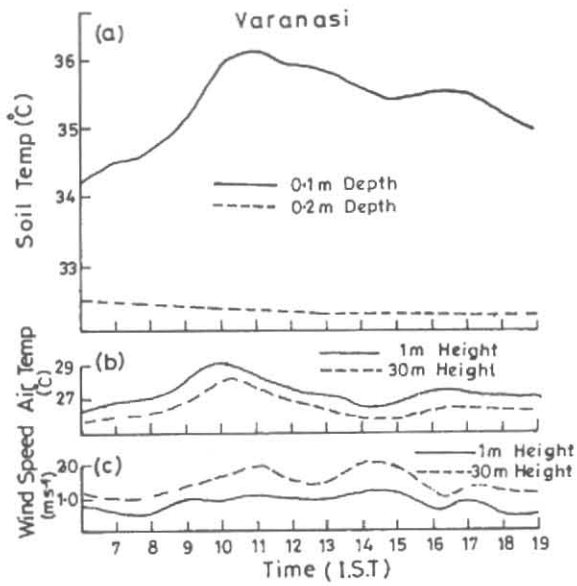



Fig. 2. Daily variation of M.S.L. pressure during July 1990

humidity. Surface layer of 30m thickness has been divided into two equal sub-layer *i.e.*, 1-15m and 15-30 m. Using the derived parameters, hourly sensible and latent heat flux are computed at 1 and 15 m height.

Soil heat flux is computed using force restored method derived by Bhumralkar (1975). There is possibility that soil heat flux either go into (+) soil or come out (−) of it. Soil physical parameter are taken into consideration and computation is done using the following relation (Watnabe, 1994).

$$\mathrm{GH} = \left(\frac{C\lambda}{2\omega}\right)^{1/2}\left[\frac{\partial T}{\partial t} + \omega\,(\overline{T_s} - \overline{T})\right] \qquad (9)$$




Figs. 3(a-c). Diurnal variation of mean meteorological parameters (a) Soil temp. (°C), (b) Air temp. (°C) and (c) Wind-speed ($ms^{-1}$) at Varanasi on 3 July 1990

Where, C= Soil heat capacity ($2.64\times10^{6}$ $Jm^{-3}K^{-1}$),

$\lambda$ = Soil heat conductivity (0.47 $Wm^{-1}$ $K^{-1}$),

$\overline{T_s}$ = Hourly value of ground temperature.

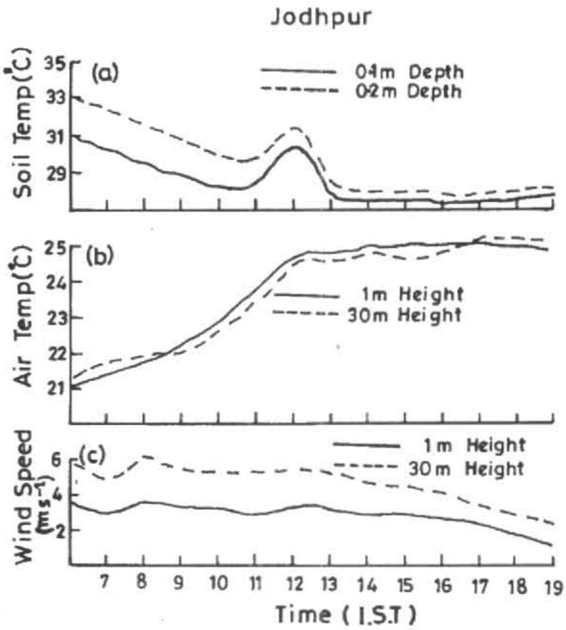
In view of visualizing the results, all downward fluxes are considered as positive (+) and upward fluxes as negative (−).

## 4. Variation of weather elements

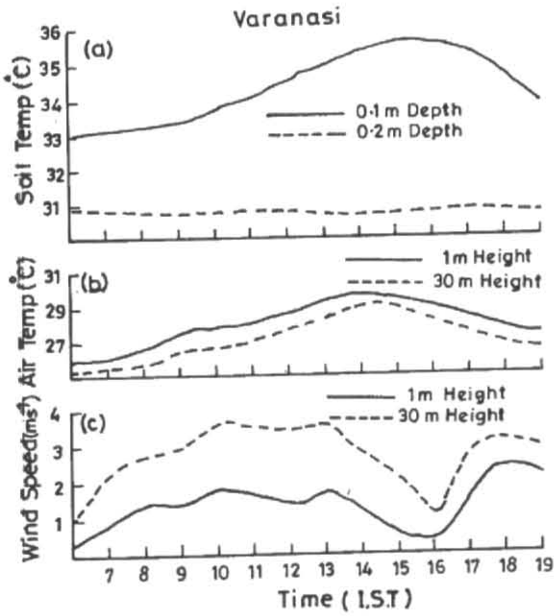
### 4.1. *Daily variation*

#### 4.1.1. *Maximum temperature*

Day-to-day variation of maximum temperature during July 1990 is shown in Fig. 1. The highest maximum temperature was 38.6° C on 2 and the lowest was 25.5° C on 3 July 1990 at Jodhpur. Similarly the highest was 33.6° C on 7 and the lowest was 27.4° C on 30 July 1990 at Varanasi. It was observed that the temperature at Varanasi was always less than that of Jodhpur except a few days in the first week. Maximum temperature was observed as 30.4, 32.0, 31.5 and 33.6° C at Varanasi and 25.5, 35.0, 35.4 and 37.2° C at Jodhpur on 3,12,21, and 24 July 1990 respectively. Daily maximum temperature indicates that incoming solar radiation was greater at Jodhpur than that of Varanasi from 9-31 July 1990.




**Figs. 4(a-c).** Diurnal variation of mean meteorological parameters (a) Soil temp. (°C), (b) Air temp. (°C) and (c) Wind speed (ms$^{-1}$) at Jodhpur on 3 July 1990




**Figs. 5(a-c).** Diurnal variation of mean meteorological parameters (a) Soil temp. (°C), (b) Air temp. (°C) and (c) Windspeed (ms$^{-1}$) at Varanasi on 21 July 1990

4.1.2. *Mean sea level pressure*

Pressure pattern at Varanasi and Jodhpur is shown in Fig. 2. Rising and falling pressure tendency follow each other at both the station except a few days. The lowest and the highest value were reported as 992.0 and 1000.5 hPa on 4 and 15 July 1990 at Jodhpur and 994.7 and 1001.6 hPa on 2 and 7 July 1990 at Varanasi respectively. The pressure was observed as 995.6, 997.0, 997.3 and 988.7 hPa at Varanasi and 993.4, 998.9, 996.2 and 998.1 hPa at Jodhpur on 3,12,21 and 24 July 1990 respectively. In the first week of July 1990, the value was found in the range of 992.0 – 1000.3 hPa at Jodhpur and 994.7 – 1001.6 hPa at Varanasi.

4.2. *Hourly variation*

4.2.1. *Soil temperature, air temperature and wind-speed*

Soil temperature, air temperature and windspeed of Varanasi and Jodhpur on 3 July 1990 are shown in Figs. 3 and 4. At Varanasi rising soil temperature attained the highest value 36.2°C at 1100 IST at 0.1m depth thereafter fell continuously till 1900 IST whereas at 0.2m depth fall was negligible. At Jodhpur, soil temperature at 0.1 and 0.2m depth differs remarkably with that of Varanasi. It is found that the temperature at 0.2m depth is higher than that of 0.1m depth at Jodhpur [Fig.4(a)]. whereas such type of soil thermal structure was not observed at Varanasi [Fig. 3(a)]. Air temperature at 1 and 30m height is depicted for both the station in [Figs 3(a) & 3(b)]. The temperature at 30m height is less than that of 1 m at Jodhpur from 0900-1700 IST whereas at Varanasi and temperature at 1m height is greater than that of 30 m throughout the day. The highest air temperature was recorded as 28.8°C and 25.0°C at 1m height at Varanasi and Jodhpur respectively. Windspeed was observed variable at Varanasi while it was found decreasing at Jodhpur. The highest windspeed at 30m height was 6.0 and 1.8 m/s at Jodhpur (0800 IST) and Varanasi (1400 IST) respectively [Figs. 3(c) & 4(c)].

Similarly, Figs. 5 and 6 show soil temperature, air temperature and windspeed for both the stations on 21 July 1990. Systematic rise of soil temperature was recorded at both the stations from 0600 IST especially at 0.1 m depth, however, at Varanasi the temperature fell beyond 1600 IST [Figs. 5(a) & 6(a)]. The highest was recorded as 38.5°C at Jodhpur at 1700 IST and 35.5°C at 1500 IST at Varanasi at 0.1m depth. It is nearly unchanged at 0.2m depth at Varanasi while at Jodhpur there is a rising tendency from 1300 IST. Generally hourly value of ground temperature was found highest at

**TABLE 2**

**Hourly ground temperature (°C) during July 1990**

| Time (IST) | Varanasi | | | | Jodhpur | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 July | 12 July | 21 July | 24 July | 3 July | 12 July | 21 July | 24 July |
| 0600 | 37.5 | 37.6 | 36.8 | 38.9 | 28.4 | 36.0 | 37.2 | 38.9 |
| 0700 | 38.1 | 38.1 | 37.5 | 41.0 | 30.4 | 37.3 | 38.2 | 39.8 |
| 0800 | 38.5 | 38.7 | 38.1 | 43.1 | 32.3 | 38.5 | 39.2 | 40.6 |
| 0900 | 38.9 | 39.1 | 38.6 | 44.8 | 33.9 | 39.5 | 40.1 | 41.3 |
| 1000 | 39.2 | 39.5 | 39.0 | 46.2 | 35.2 | 40.3 | 40.7 | 41.8 |
| 1100 | 39.4 | 39.7 | 39.2 | 47.0 | 36.0 | 40.8 | 41.2 | 42.2 |
| 1200 | 39.5 | 39.8 | 39.3 | 47.4 | 36.3 | 41.0 | 41.3 | 42.3 |
| 1300 | 39.5 | 39.7 | 39.3 | 47.1 | 36.1 | 40.9 | 41.2 | 42.3 |
| 1400 | 39.3 | 39.5 | 39.0 | 46.3 | 35.3 | 40.4 | 40.8 | 41.9 |
| 1500 | 38.9 | 39.2 | 38.6 | 45.0 | 34.1 | 39.6 | 40.2 | 41.4 |
| 1600 | 38.6 | 38.7 | 38.1 | 43.4 | 32.6 | 38.6 | 39.4 | 40.7 |
| 1700 | 38.1 | 38.2 | 37.6 | 41.4 | 30.7 | 37.5 | 38.4 | 39.9 |
| 1800 | 37.6 | 37.7 | 37.2 | 39.2 | 28.7 | 36.2 | 37.3 | 39.0 |
| 1900 | 37.1 | 37.1 | 36.8 | 37.0 | 27.5 | 34.9 | 36.3 | 38.1 |

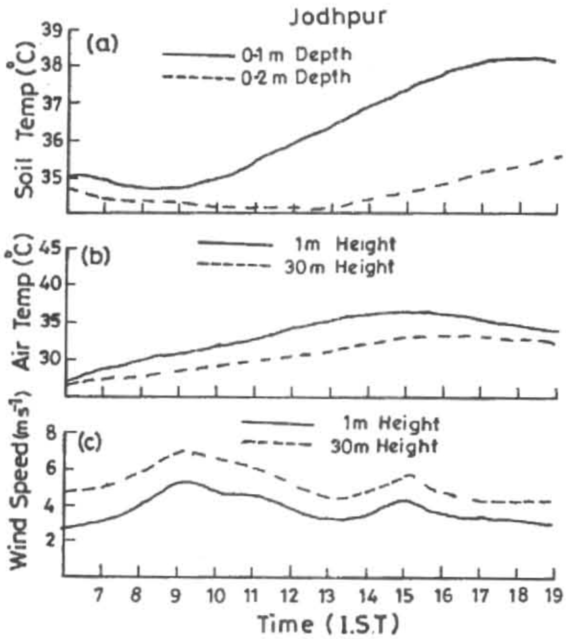
1200 IST at both the station (Table 2). The highest air temperature was 29.8°C and 36.3°C at Varanasi and Jodhpur respectively at 1400 IST [Figs. 5(a) & 6(b)]. The highest soil temperature was observed within two hours of occurrence of maximum air temperature. It is imputed that energy flux accumulates in the soil from mid-day which leads to the highest soil temperature at 0.1m depth within four hours during non-rainy days. Windspeed throughout the day at 30m was greater than that of 1m height at both the stations. The highest windspeed was 3.8 m/s at Varanasi at 1000 IST and 7.5m/s at Jodhpur at 0900 IST at 30 m height [Figs.5 (c) & 6(c)].

4.2.2. *Global radiation*

Fig. 7 shows average global radiation in July 1990 at Varanasi and Jodhpur. The highest value of the radiation was recorded as 666.5 and 444.4 $Wm^{-2}$ at 1200 IST at Jodhpur and Varanasi respectively thereafter gradually decreased. Hourly value of the radiation was greater at Jodhpur than Varanasi during the month. At 0700 IST value of the radiation was found as 55.5 and 111.1 $Wm^{-2}$ and at 1800 IST the same was 83.3 and 138.9 $Wm^{-2}$ at Varanasi and Jodhpur respectively. Flux of the radiation was 870.1 $Wm^{-2}$ on 12 while it was 41.7 $Wm^{-2}$ on 3 July 1990 at 1300 IST at Jodhpur. Similarly, magnitude of the flux was 619.4 $Wm^{-2}$ on 12 and 166.8 $Wm^{-2}$ on 3 July 1990 at Varanasi at 1300 IST. In such a manner incident global radiation on 21 July 1990 was also examined and found that these were 505.9 and 636.6 $Wm^{-2}$ at 1400 IST at Varanasi and Jodhpur respectively. In fact prevailing cloud amount is an important reducing element of incoming short wave radiation (Table 1). Diurnal variability of cloud brings about definite changes to incoming amount of the radiation. The effect of the changes is certainly related with net radiation *vis-a-vis* energy fluxes which balance the radiation budget in the surface layer. Temporal and spatial variation of cloud coverage modify the magnitude of the components of net radiation on an average basis (Minnis and Harrison, 1984).

4.3. *Average soil temperature*

Daily average soil temperature is shown in Fig. 8 for each layer which was computed from hourly data. The temperature decreases with depth at Varanasi on 3, 12 and 21 July 1990 whereas there is rise by 0.3 °C at 0.1m




**Figs. 6(a-c).** Diurnal variation of mean meteorological parameters (a) Soil temp. (°C), (b) Air temp. (°C) and (c) Wind speed ($ms^{-1}$) at Jodhpur on 21 July 1990

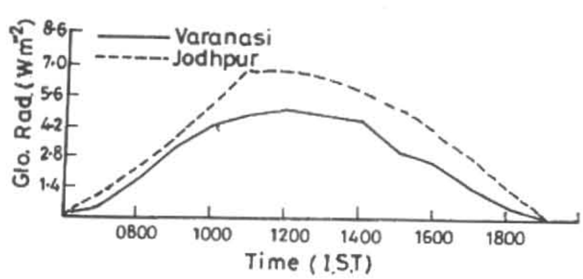
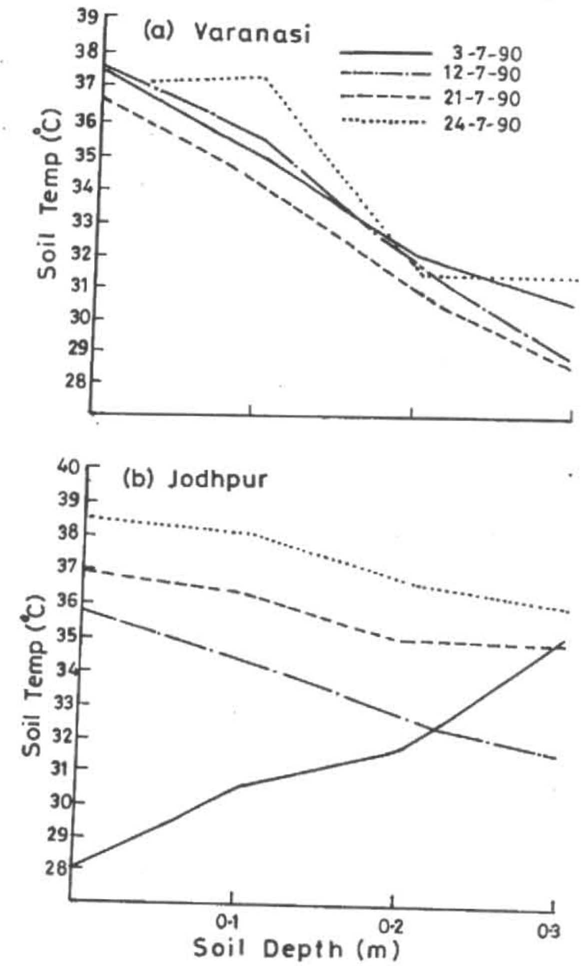



**Fig. 7.** Diurnal variation of global radiation during the month of July 1990

depth thereafter fall by 5.8°C at 0.2 m depth on 24 July 1990 at Varanasi [Fig. 8(a)]. Similar characteristic was also found at Jodhpur except 3 July 1990 [Fig. 8(b)]. There was rain on 3 July 1990 from 1420-1940 IST at Varanasi and 0145-1938 IST at Jodhpur though soil thermal structure differs with each other. Averages of temperature are 28.1, 30.5, 31.7 and 35.5° C at Jodhpur and 37.5, 35.0, 32.4 and 30.5° C at Varanasi on 3 July 1990 for ground 0.1, 0.2 and 0.3 m depth respectively. In addition averages of the temperature for other days are also examined to ascertain the profile during rain at both the stations. Averages of the temperature are 39.8, 39.1,



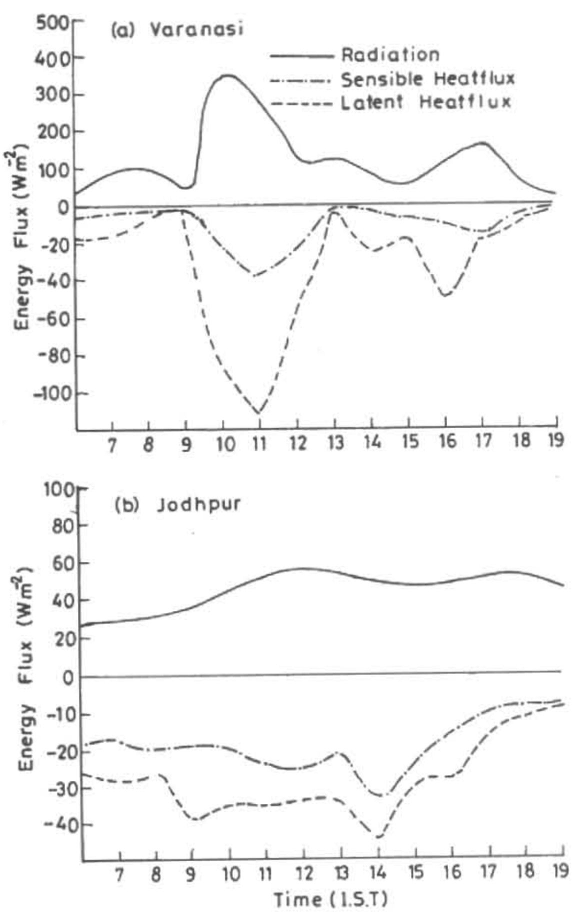

**Figs. 8(a&b).** Average soil temperature at (a) Varanasi (b) Jodhpur on 3 July 1990 (—), 12 July 1990 (- · -), 21 July 1990 (----) and 24 July 1990 (........)

37.3 and 37.4°C at Jodhpur for ground 0.1, 0.2 and 0.3 m depth respectively on 2 July 1990 at Varanasi the value is 37.8, 35.6, 32.6 and 30.9°C on 1 July 1990 for the same levels inspite of rain.

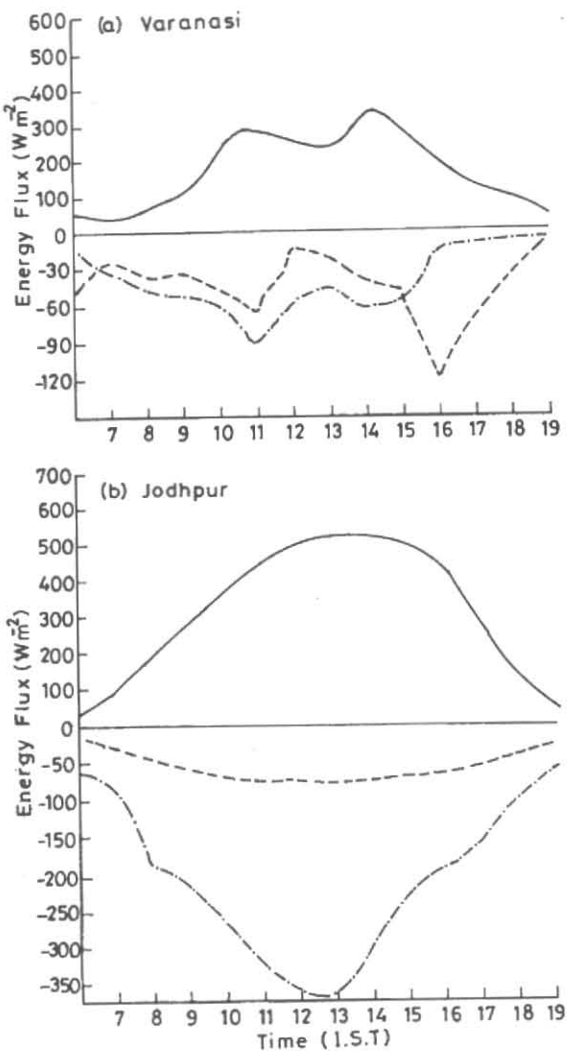
## 5. Diurnal variation of energy fluxes

### 5.1. *Net radiation, sensible and latent heat*

Fig. 9 displays hourly variation of net radiation, sensible and latent heat on 3 July 1990 at Varanasi and Jodhpur. The highest net radiation is 335.9 $Wm^{-2}$ at 1000 IST at Varanasi on 3 July 1990 and at the same time sensible and latent heat are 20.7 and 91.3 $Wm^{-2}$ [Fig.9(a)]. The fluxes decrease with increase in cloudiness and commencement of rain. At Jodhpur, the highest net radiation is 58.6 $Wm^{-2}$ at 1200 IST and




**Figs. 9(a&b).** Diurnal variation of net radiation (—), sensible heat flux (—·— ), and latent heat flux (----) at (a) Varanasi and (b) Jodhpur on 3 July 1990




**Figs. 10(a&b).** Diurnal variation of net radiation (—), sensible heat flux (—·—), and latent heat flux (-----) at (a) Varanasi and (b) Jodhpur on 21 July 1990

simultaneously sensible and latent heat are 21.1 and 34.2 Wm$^{-2}$. Sensible and latent heat decrease after 1400 IST and show a little increase between 0600-1400 IST [Fig. 9(b)] because windspeed was found to be steady and temperature gradient between two consecutive layer is small and invariable [Fig. 4(c)] . Sensible heat varies in the range of 9.3 – 36.1 Wm$^{-2}$ while latent heat varies between 10.3 - 45.6 Wm$^{-2}$ on 3 July 1990 at Jodhpur. Temporal variability of net radiation is more important than its spatial variability in changing local flux of sensible and latent heat (Smith *et al.* 1994). During rainy days sensible heat is found less than the latent heat flux.

There was rain between 1620-1705 IST at Varanasi on 21 July 1990 whereas no rain at Jodhpur. The value of net radiation increases from 0600 IST and decreases after 1400 IST (Fig. 10). Latent heat exceeds to sensible heat at Varanasi just after 1500 IST and maintains increasing trend till cessation of rain [Fig. 10(a)]. Sufficient moistures is built up with rain, consequently major part of available net radiation is transformed into latent heat. Indeed, there are two peaks of net radiation at Varanasi on 21 July 1990 –one peak occurs at 1100 IST and another at 1400 IST. It is believed that maxima splits into two peaks due to increase in cloudiness from 1100-1300 IST over the station. The highest net radiation was obtained as 268.3 Wm$^{-2}$ at 1100 IST and 354.8 Wm$^{-2}$ at 1400 IST and associated sensible and latent heat at 1100 IST are 90.5 and 60.5 Wm$^{-2}$ and at 1400 IST 60.9 and 40.6 Wm$^{-2}$

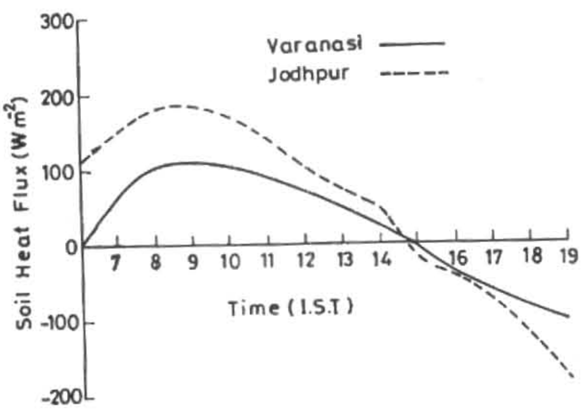



**Fig. 11.** Diurnal variation of soil heat flux at Varanasi (—) and Jodhpur (-----) on 3 July 1990

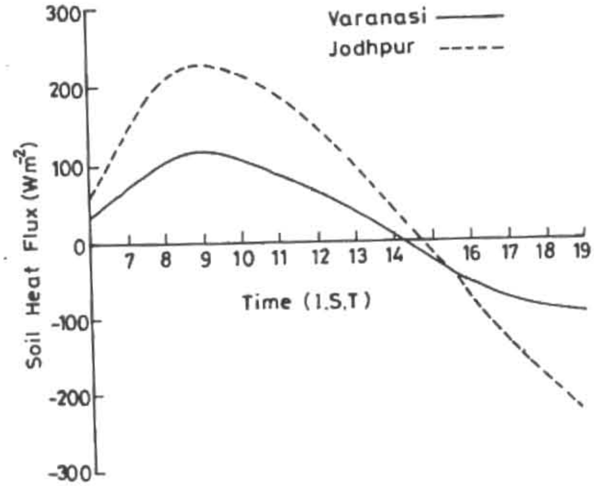



**Fig. 12.** Diurnal variation of soil heat flux at Varanasi (—) and Jodhpur (-----) on 21 July 1990

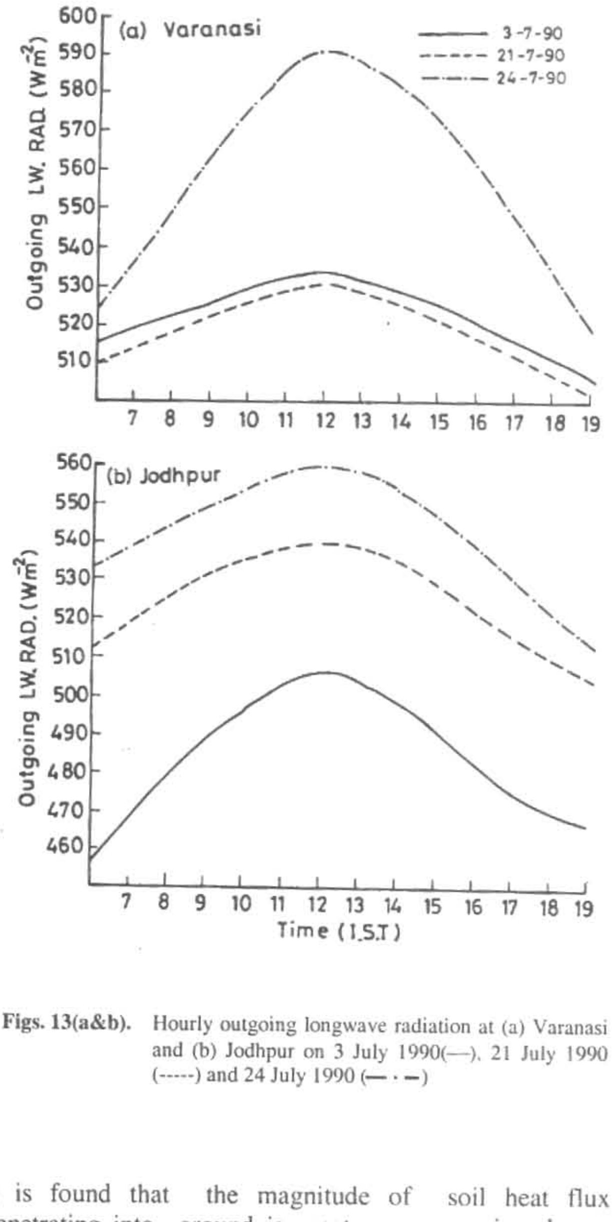
respectively. Later on the fluxes decrease with decrease in net radiation. At Jodhpur, uninterrupted rise of net radiation is found and reaches to maximum 510.1 Wm$^{-2}$ on 21 July 1990 [Fig. 10(b)] *vis-à-vis* sensible and latent heat flux are found as 368.4 and 50.0 Wm$^{-2}$ respectively. Sensible, latent heat and net radiation follow each other throughout the day and are maintaining the consistency of diurnal cycle during non-rainy day. Moisture availability is one of the most important factor which plays a crucial role in exchanging available energy into various components of surface energy fluxes (McCumber and Pielke, 1981). Similar nature of the fluxes are also found on other non-rainy days.

5.2. *Soil heat flux*

Fig. 11 shows hourly variation of soil heat flux at Varanasi and Jodhpur on 3 July 1990. The flux is directed upward at Jodhpur and Varanasi between 1500-1900 IST and varies between 8.4-102.6 Wm$^{-2}$ at Varanasi and 22.6-175.1 Wm$^{-2}$ at Jodhpur. Value of the highest downward flux is 107.2 and 187.4 Wm$^{-2}$ at Varanasi and Jodhpur respectively at 0900 IST. The sign of the flux is unaffected by prevailing weather element such as wind, temperature and relative humidity in the surface layer. It was found that there was fall in air and soil temperature from 1100 IST at Varanasi (Fig. 3). Ground temperature are found as 39.4°C and 39.3°C at 1100 and 1400 IST respectively (Table 2) while average soil temperature at 0.1 m depth is 36.2°C at 1100 IST and 35.6°C at 1400 IST on 3 July 1990. Similarly, air temperature rises to 28.6°C at 1100 IST which falls to 26.6° C at 1400 IST at 1 m above the ground. Relative humdity varies in the range of 97-100% between 1100-1400 IST at 1 m above the ground. Windspeed changes in the range of 0.99-1.30 m/s for the same height between 1100-1400 IST [Fig. 3 (c)].

The soil characteristic and interactive behaviour changes during non-rainy days and feedback mechanism for the physical processes in the atmosphere is enchanced by dry soil. In moisture stress condition, the flux becomes more intense and penetrates into soil during daytime between 0600-1400 IST on 21 July 1990 (Fig. 12). Direction of the flux is upward between 1500-1900 IST at both the station. Reversal of sign is not accompanied with rain event and increase in relative humidity at ground. Average relative humidity was found in the range of 70-83% between 0600-0800 IST at Jodhpur which decreased to less than 70% during mid-day. The highest downward flux is 113.8 and 225.9 Wm$^{-2}$ at Varanasi and Jodhpur at 0900 IST respectively. Similarly, the highest value of the downward flux is computed as 287.4, 189.9, 353.8, 273.8 and 388.9 Wm$^{-2}$ on 2, 11, 12 and 24 July 1990 at Jodhpur and 225.9, 121.1 and 463.9 Wm$^{-2}$ on 1, 12 and 24 July 1990 respectively at Varanasi.

Evaporative power of atmosphere depends on wind-speed, air temperature and relative humidity. Averages of surface layer relative humidity are found as 94 and 90% at Varanasi and at Jodhpur 71% and 63% on 3 and 21 July 1990 respectively. There was rain on 3 July 1990 at both the station while rain was not reported on 21 July 1990 at Jodhpur (Table 1). Daily averages of the downward flux are computed as 129.2 and 164.7 Wm$^{-2}$ at Jodhpur and 68.2 and 82.1 Wm$^{-2}$ at Varanasi on the same days. Similarly, results pertaining to other days are also analyzed with a view to ensure direction and magnitude of the flux during rainy and non-rainy days. On comparison




**Figs. 13(a&b).** Hourly outgoing longwave radiation at (a) Varanasi and (b) Jodhpur on 3 July 1990(—), 21 July 1990 (-----) and 24 July 1990 (— · —)

it is found that the magnitude of soil heat flux penetrating into ground is greater on non-rainy day at both the station than rainy day.

### 5.3. *Outgoing longwave radiation*

Fig. 13 shows hourly variation of the upward infrared radiation leaving the earth's surface on 3, 21 and 24 July 1990 for both the stations. Diurnal variation of the radiation is less on 3 and 21 July 1990 than 24 July 1990 at Varanasi because of rain during day time. Hourly value of OLR lies in the range of 521.5-541.6 and 508.3-548.9 Wm$^{-2}$ on 12 July 1990 at Varanasi and Jodhpur respectively. Diurnal variation is maximum on 24 July 1990 at both the stations. The highest value of the radiation is 592.9 Wm$^{-2}$ at 1200 IST and the lowest is 521.8 Wm$^{-2}$ at 1900 IST at Varanasi [Fig. 13 (a)] whereas the highest and lowest value are 556.3 and 528.6 Wm$^{-2}$ at 1200 and 1900 IST respectively at Jodhpur [Fig. 13(b)].

Surface relative humidity is an important factor which also bring about some changes to OLR value in combination with windy condition. Averages of relative humidity are found as 57, 71, 81, 80, 72, 63 and 72% on 2, 3, 9, 11, 12, 21 and 24 July 1990 at Jodhpur respectively and daily value of OLR is computed as 544.3, 477.4, 481.9, 523.4, 517.7, 523.9 and 537.5 Wm$^{-2}$ on the same days. Similarly at Varanasi averages of relative humidity are 94, 94, 92, 90 and 85% and daily value of OLR is 532.2, 522.1, 523.3, 528.7 and 537.5 Wm$^{-2}$ on 1, 3, 12, 21 and 24 July 1990 respectively. The largest and smallest value have been examined and found that the daily mean ranges from 497.4 – 548.4 Wm$^{-2}$ at Varanasi and 473.0 – 537.6 Wm$^{-2}$ at Jodhpur. Mean coefficient of ranges is also computed and found as 0.04 and 0.06 at Varanasi and Jodhpur respectively. Thus, the variability of OLR in moist convective zone is found less than dry convective zone.

Observation shows that surface relative humidity increases with increase in low and medium cloud coverage. Estimate of day-to-day variability of cloud cover and relative humidity have been examined to describe the effect on OLR. It is found that the dip is increased by 10% in cloudiness and high relative humidity (Thompson and Warren, 1982, Ramanathan, 1977 and Warren and Thompson, 1983). Computed value of ground temperature is found the highest on 24 July 1990 at Varanasi and Jodhpur. The highest ground temperature is computed as 47.4°C and 42.3°C at 1200 IST at both the stations (Table 2). Sky was generally cloudy and there were no rain during day time while on other days there was mainly cloudy sky (Table 1). Modulation of OLR is found to be prominent in case of rising temperature and reducing surface humidity alongwith cloud amount (Yang *et al.* 1987).

## 6. Radiation budget

Hourly and daily value of the fluxes are examined to explain partitioning of net radiation into various components together with energy budget on the ground. Value of net radiation is 494.2 and 407.3 Wm$^{-2}$ on 24 July 1990 at 1200 IST at Varanasi and Jodhpur respectively. Sensible, latent and soil heat flux are computed as 0.21Rn, 0.16Rn and 0.42 Rn at 1200 IST at Varanasi. Least percentage of latent heat flux signifies moisture stress condition on the ground. In another case, value of the radiation is 426.2 and 603.5 Wm$^{-2}$ on 12 July 1990 at 1300 IST at Varanasi and Jodhpur respectively. Sensible, latent and soil heat are found as 0.11Rn, 0.20Rn and 0.09Rn at Jodhpur and 0.06Rn, 0.47Rn and 0.05Rn respectively at Varanasi. Flux of latent heat is found to be more than the sensible heat at both the stations because of rain (Table 1). In such a manner various other cases have also been analyzed and found that exact balance has not been achieved between net radiation and non-radiative fluxes. Mostly sum of the hourly fluxes are less than the net radiation by 40-50%.

In view of balancing the energy equation cumulative value of net radiation and the fluxes from 0600-1900 IST are considered. Value of the cumulative net radiation is 1627.7 and 726.6 $Wm^{-2}$ on 3 July 1990 at Varanasi and Jodhpur respectively *vis-à-vis* sensible, latent and soil heat are 0.12Rn, 0.30Rn and 0.56Rn at Varanasi and 0.30Rn, 0.45Rn and 0.68Rn at Jodhpur respectively. Similarly, value of cumulative net radiation is 2377.8 and 4185.5 $Wm^{-2}$ at Varanasi and Jodhpur respectively on 21 July 1990 and corresponding sensible, latent and soil heat are found as 0.24Rn, 0.28Rn and 0.43Rn at Varanasi and 0.55Rn, 0.04Rn and 0.45Rn at Jodhpur. Like wise, partitioning of net radiation into non-radiative fluxes are also examined for different days and found that cumulative energy fluxes nearly balance the net radiation. However, on some of the occasions fluxes are either overestimated or underestimated by ± 30-40% of net radiation only during rainy days.

## 7. Conclusions

(*i*) Averages of OLR vary in the range 473.0-537.6 $Wm^{-2}$ at Jodhpur and 497.4-548.4 $Wm^{-2}$ at Varanasi during generally cloudy day. Diurnal variability of the radiation has been found largest over dry convective zone.

(*ii*) Surface layer relative humidity alone do not have significant impact in dipping OLR. The dip is increased by 10% with rain and increase in cloud cover and relative humidity.

(*iii*) The highest value of downward soil heat flux attains around 0900-1000 IST and sign of the flux reverse around 1400-1500 IST and thereafter becomes upward during rainy and non-rainy days. About 40-50% of net radiation is converted into soil heat flux at both the stations.

(*iv*) Conversion of net radiation into sensible, latent and soil heat flux is controlled by prevailing local weather condition. Sensible, latent and soil heat flux are found as 0.12Rn, 0.38Rn and 0.50Rn at Varanasi and 0.22Rn, 0.37Rn and 0.41Rn at Jodhpur during non-rainy day.

(*v*) Turbulent exchange of sensible and latent heat flux is suppressed during rain while flux of OLR and soil heat continue to exist uninterruptably. Hence, soil heat and OLR may be considered as potential energy source to atmosphere during rainy day.

(*vi*) Daily mean of the largest downward soil heat flux has been found as 206.4 and 269.4 $Wm^{-2}$ at Varanasi and Jodhpur respectively during generally cloudy day.

(*vii*) Hourly net radiation is not balanced by non-radiative fluxes instantaneously while daily net radiation (cumulative) ia balanced by sum of non-radiative fluxes during non-rainy day. However, the balance is not achieved during rainy day.

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