Pergamon

Atmospheric Environment Vol. 29, No. 16, pp. 2113–2129, 1995

1352-2310/95 $9.50 + 0.00

1352-2310(94)00363-7

TURBULENT HEAT FLUX VARIATION OVER THE MONSOON-TROUGH REGION DURING MONTBLEX-90

KUSUMA G. RAO,* SETHU RAMAN,† A. PRABHU‡ and R. NARASIMHA‡

*Jawaharlal Nehru Centre for Advanced Scientific Research, Indian Institute of Science Campus; Bangalore 560012, India; †Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695-8208, U.S.A.; and ‡Centre for Atmospheric Sciences, Indian Institute of Science, Bangalore 560012, India

(*First received* 20 *January* 1993 *and in final form* 1 *October* 1994)

Abstract—Tower data collected during the Monsoon-Trough Boundary Layer Experiment (MONTBLEX-90) have been analysed to understand the observed structure of the surface layer over an arid region (Jodhpur) and a moist region (Kharagpur) during active and weak phases of the 1990 southwest monsoon. Turbulent heat and momentum fluxes are estimated by the eddy correlation method using sonic data. The turbulent momentum flux at both Jodhpur and Kharagpur was larger when the winds were stronger, reaching a maximum of the order of 0.5 N m^{-2} on 5 and 6 August when a low pressure system was located over the region. The heat flux at Jodhpur is high during weak monsoon days, the maximum being 450 W m^{-2}, whereas during active days the flux never exceeds 200 W m^{-2}. At Kharagpur, the flux does not vary significantly between active and weak monsoon days, the maximum in either phase being 160 W m^{-2}. At Jodhpur, there is significant contrast in the near-surface air temperature, being higher during weak monsoon days as compared to active days. Cloud cover did not vary significantly in both the regions. The turbulent heat flux variation at both the sites appears to be correlated mainly with soil mixture, and less sensitive to cloud cover.

Key word index: Heat flux, monsoon, MONTBLEX.

1. INTRODUCTION

Interaction between the atmospheric boundary-layer and the climate depends on the nature of the underlying surface and the presence of clouds in the atmospheric boundary layer. The atmospheric boundary layer controls the evaporation and the distribution of clouds in the boundary layer, which in turn determines the radiative forcing of the climate system. On the other hand, climate influences the mean climatological structure of the atmospheric boundary layer because of the increased carbon dioxide concentration via the longwave radiative fluxes. Also an increase in the mean temperature associated with climate change influences the surface sensible and latent heat fluxes.

The southwest monsoon is a quasi-permanent annual feature of the circulation over the Indian subcontinent, characterized by a variety of time scales over which the monsoon rainfall fluctuates. Within the monsoon season two phases can be identified: an active phase associated with widespread and substantial rainfall; and a weak phase associated with deficient rainfall over almost the entire subcontinent except near the foothills of the Himalayas and a small region in southeast India. There are several observational studies of the large-scale aspects of monsoon variability (e.g. Yasunari, 1979; Krishnamurti and Subramanyanam, 1982); but little emphasis has been placed on understanding the role of the atmospheric boundary layer over the monsoon trough region which is crucial in explaining the monsoon variability between active and break phases of monsoon. There are some studies describing the thermodynamic structure of the boundary layer, and the variation of its height and the heat flux over the Indian land region by Sivaramakrishnan *et al.* (1992), Raman *et al.* (1990), Parasnis (1991), Kusuma *et al.* (1991) and Kusuma (1986). Thus Kusuma *et al.* (1991) described the thermodynamic structure and indicated significant variation in the boundary layer heights during the active and break periods of the 1979 monsoon using upper airdata. Kusuma's (1986) computations of the sensible heat flux based on Saltzman–Ashe (1976) parameterization, during active and break monsoon periods using upper air data, suggested that the sensible heat flux was larger during a break than in the active period almost everywhere over the Indian land region.

In the present paper, our main aim is to compute the contrasting mean structure of the surface layer using fast turbulence data during active and weak periods over the monsoon trough region, in the light of the recent observations during MONTBLEX 1990

(Goel and Srivatsava, 1990). This national experiment conducted during the southwest monsoon of 1990 has provided extensive data including turbulence as well as many other parameters from various instruments and satellites over both land and the oceans. Sivaramakrishnan *et al.* (1992) have analysed the data collected during a pilot experiment at Kharagpur (22.3°N, 87.2°E) (known as MONTBLEX 1989) for the days 6–8 July 1989 during the southwest monsoon season. They calculated turbulent heat and momentum fluxes by the eddy correlation method and verified that the Monin–Obukhov similarity is valid. Raman *et al.* (1990) computed the boundary layer height variation (using miniradio sonde data) and the heat flux during the premonsoon and monsoon periods during 1987 using the micrometeorological tower data at two stations, namely New Delhi and Bangalore. Here we have computed the diurnal and vertical variations of time-averaged wind, temperature and humidity in the surface layer, and also four other surface layer characteristics namely roughness parameter, stability, friction velocity and friction temperature, during active and weak phases of the monsoon. The turbulent fluxes of heat and momentum are estimated by eddy correlation method. Also it is intended here to study the role of soil moisture and insolation on the observed structure of the surface layer as well as on the turbulent heat and momentum fluxes over the monsoon trough region during active and weak monsoon periods.

2. ACTIVE AND WEAK PHASES OF THE MONSOON

The period chosen for observational analysis extends from 26 July to 10 August during the summer monsoon of 1990. The charts describing the rainfall distribution over subdivisions on a weekly basis, published by India Meteorological Department (IMD), are given in Fig. 1a and b for the two weeks ending on 1 August and 8 August respectively. From Fig. 1a, we see that for many subdivisions the rainfall is scanty,

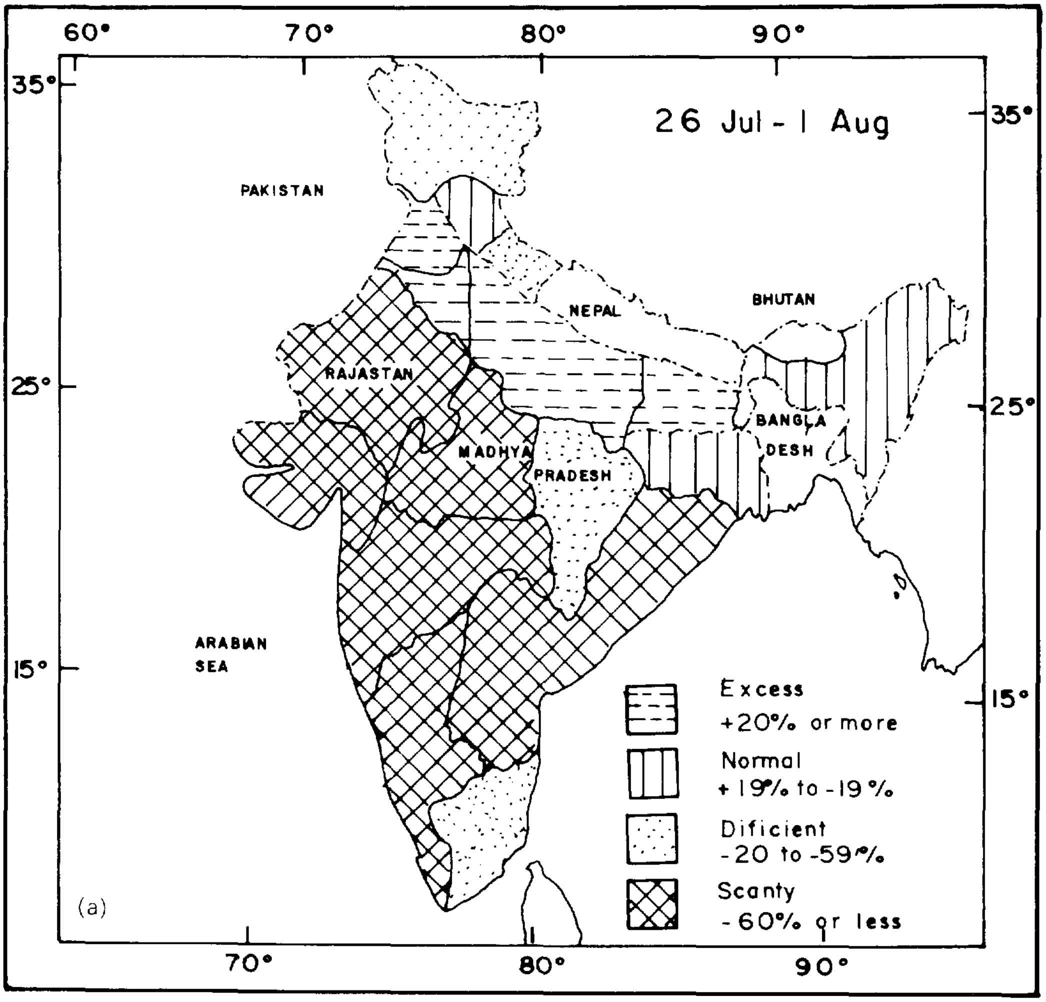

Fig. 1a.

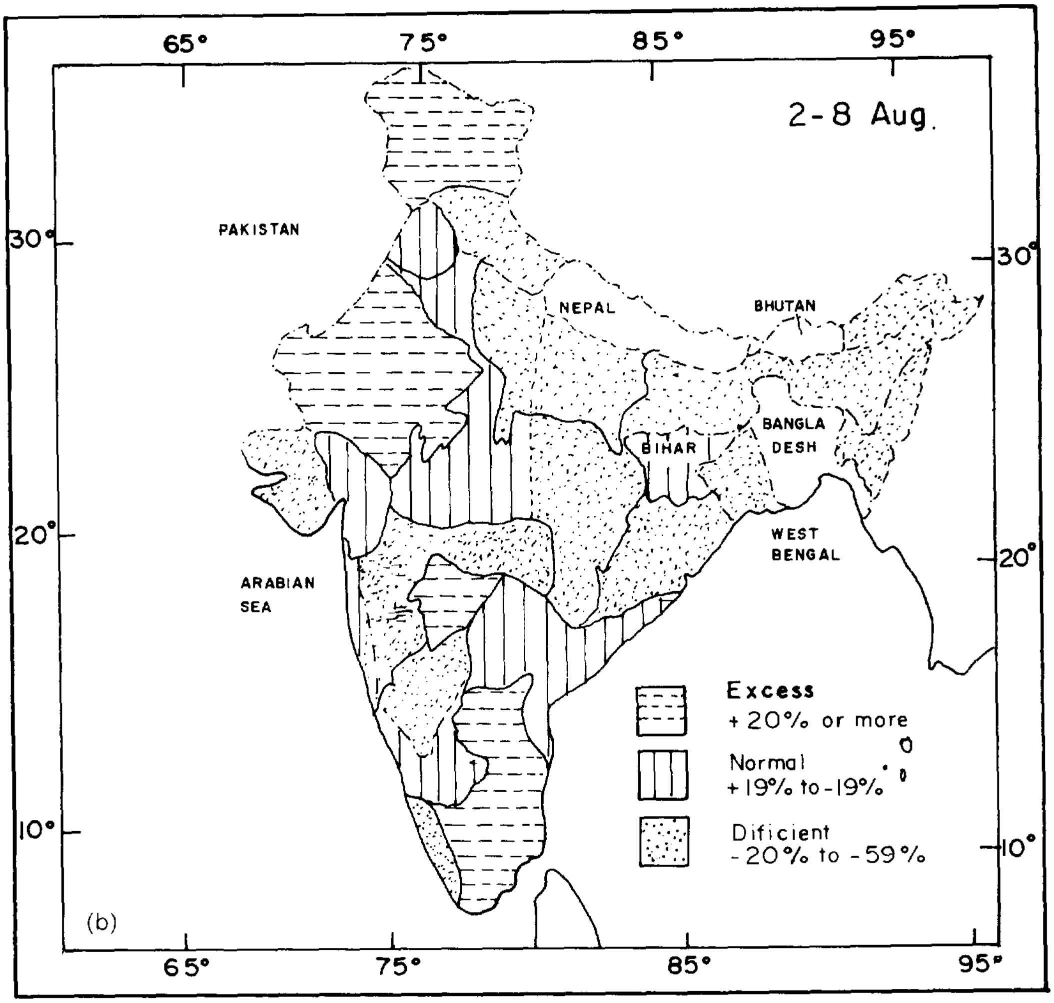

Fig. 1. Rainfall distribution over Indian subdivisions; (a) for the week ending 1 August 1990; (b) for the week ending 8 August 1990.

but excess rainfall occurs near the foothills of the Himalayas, thus indicating the break situation (Ramaswamy, 1973). Normal rainfall occurred over some of the subdivisions in the eastern Indian region. From Fig. 1b, we see that some divisions show normal to excess rainfall and some show deficient rainfall, but in no division is rainfall scanty. All subdivisions on the east except Bihar received deficient rainfall. The Weather Summary published by IMD indicates the monsoon to be weak during the week ending 1 August and active during the week ending 8 August. Seasonal monsoon trough had shifted close to the foothills of the Himalaya during the week ending 1 August suggesting a break in the monsoon (Srivastava, personal communication). Also, during 2–10 August, a low pressure area formed over northwest Madhya Pradesh and moved in the northwesterly direction and the rainfall recorded was 2–4 times the rainfall in different subdivisions of the country. This period was categorized as active (Srivastava, personal communication). Figure 2a–c show the surface pressure charts published by IMD for 29 July, 3 August and 6 August. 29 July represents weak monsoon situation and the days 3rd and 6th of August represent active monsoon condition. From Fig. 2a, on 29 July, we see that the surface pressure trough axis has shifted to the north of its mean positon. This is generally observed during breaks in monsoon (Rao, 1976). On 3 August (Fig. 2b), the trough axis has shifted to the south of its mean positon. On 6 August, a low-pressure system was located over the Rajasthan region (Fig. 2c). During the period, 5 August to 10 August, a low initially appeared over south Rajasthan, moved in a westerly direction, and finally merged with the seasonal low over south Pakistan. Figure 3 shows the satellite cloud picture for 7 August. The low over Rajasthan is obviously seen from the INSAT-1D visible satellite picture shown in Fig. 3 taken at 09 GMT on 7 August. Thus most of the prominent features generally observed during break and active periods prevailed during the periods chosen here. Next we give below the details about the data chosen for this study during the above mentioned active and weak periods.

3. DATA

Observations chosen for this study have been derived from the data set archived during the MONTBLEX 90 experiment. Figure 4 shows the MONTBLEX stations network describing the various meteorological stations over the monsoon trough region and the corresponding data availability at these stations. At four stations, namely Kharagpur, Varanasi, Delhi and Jodhpur surface layer observations were obtained using instrumented towers (Fig. 4). Details of these observations are given by Prabhu *et al.* (1990), and Rudra Kumar and Prabhu (1992). Here we have made tower data analysis for two stations namely Jodhpur (26.3°N, 73°E) and Kharagpur (22.3°N, 87.2°E) during the active and weak periods indicated above. Jodhpur being a desert station represents a dry convective region and Kharagpur a moist convective region. Towers in both sites were located in farm fields. At Kharagpur the field was covered with jungle type grass grown to a height of about 30–60 cm. At Jodhpur, the field was covered with sand and pebbles. There were some bush-type of trees in the open stretch around the Jodhpur tower.

Data selected here comprise the measurements made by cup and sonic anemometers, slow and fast temperature sensors and humicaps, all mounted on a 30 m tower. The cup anemometers were placed at six heights of the tower namely 1, 2, 4, 8, 15 and 30 m above the surface. A sonic anemometer (Model: SWS-211/3K Orthogonal Array, Applied Tech. Inc., Boulder, USA; Kaimal, 1988, 1989) was placed at a height of 4 m at Jodhpur and 8 m at Kharagpur. The slow temperature sensors, which were platinum wire thermometers, were placed at heights 1, 8, 15 and 30 m at Jodhpur; and at heights 1, 4, 15 and 30 m at Kharagpur. At heights 2 and 4 m at Jodhpur; and 2 and 8 m at Kharagpur, fast temperature sensors

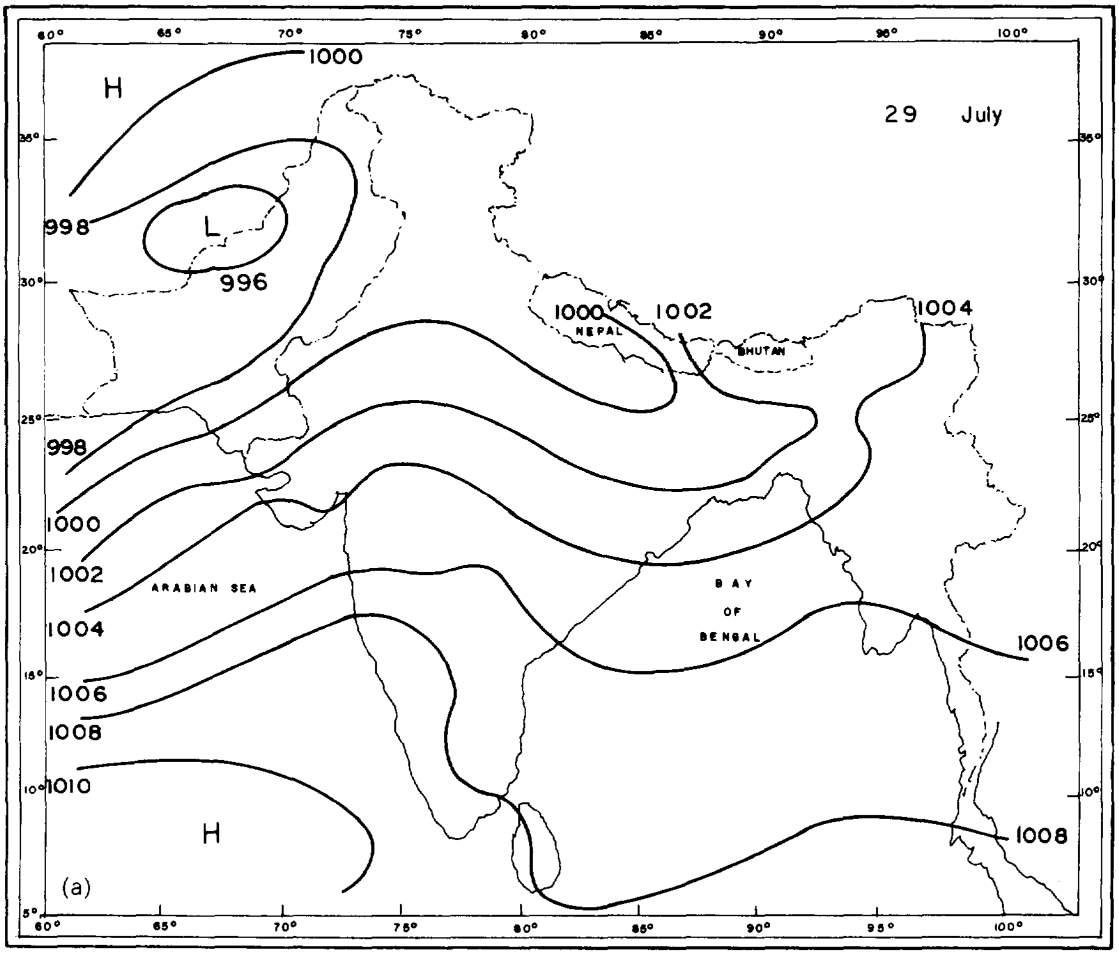

Fig. 2a.

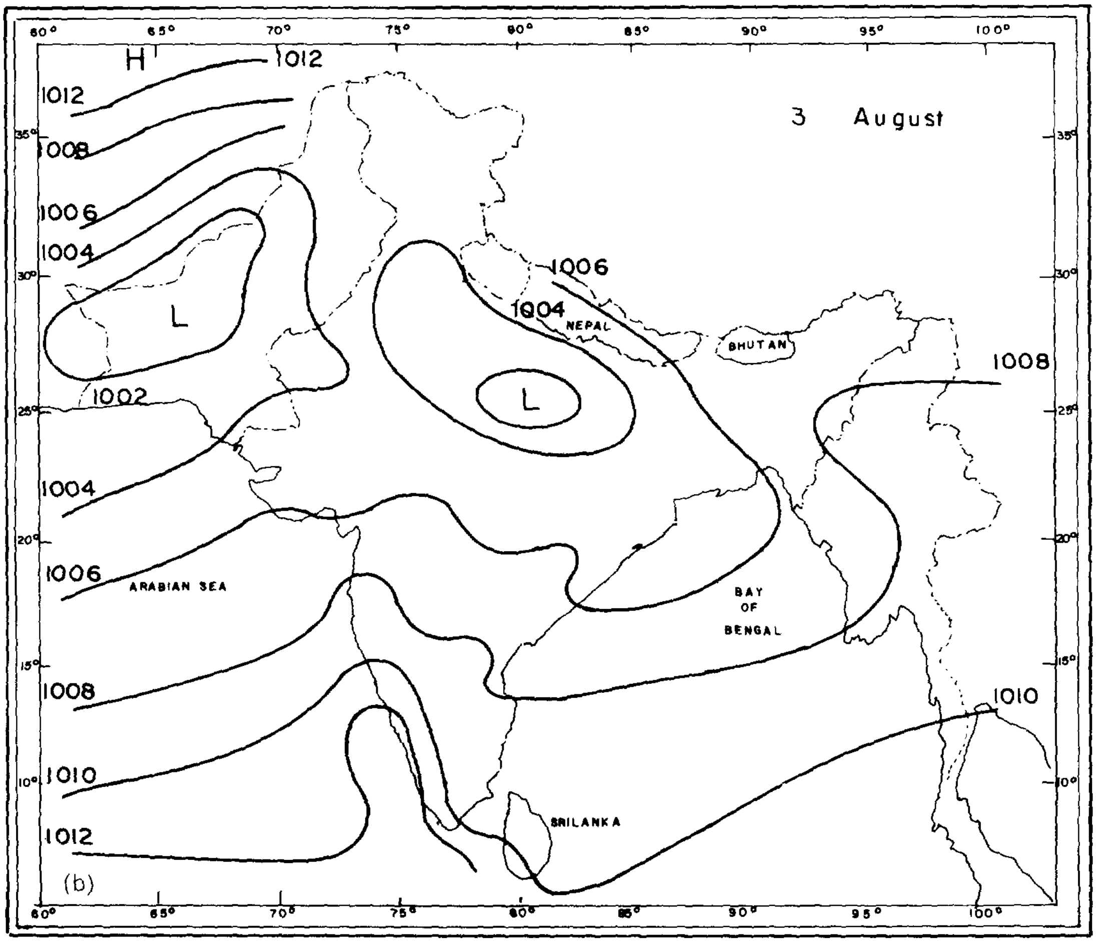

Fig. 2b.

namely platinum wires were mounted. The slow humidity sensors were placed at heights 1, 4 and 30 m at Jodhpur, and at heights 1, 8, 15 and 30 m at Kharagpur. High frequency (8 Hz) observations of turbulence and the virtual temperatures were obtained using the sonic anemometer. From the rest of the instruments mean wind speeds, temperatures and humidities were obtained. Data from all these instruments were recorded at the rate of 8 per second continuously for a sampling period of 15 min at predetermined time intervals. Number of samples during a day varied from 4 to 24. A PC-based telemetry system was used to obtain the data.

Apart from the tower data, we have used the soil temperature measured at 10 cm below the ground level and averaged over either 1 or 3 min. Also, the rainfall and cloud amount data published by local meteorological observatories at Jodhpur and Kharagpur have been used in this analysis.

Accuracy of the wind speeds measured by the sonic anemometer is about $\pm 0.05\ \mathrm{m\,s^{-1}}$, the temperature 0.05°C and the wind direction ±0.1°. A rigorous quality control procedure was adopted to ensure reliable data.

4. RESULTS

4.1. *Mean structure of diurnal variations*

Diurnal variations in temperature, humidity and wind speeds are computed by constructing the 15 min time averages of each of these variables.

Jodhpur. Figures 5a, b, 6a, b and 7 show the diurnal variations in wind, temperature and humidity at all the levels where the data are available. Figure 5a shows the diurnal variations in wind speed at all six levels during the weak days from 26 to 31 July, and Fig. 5b, during active days from 5 to 10 August. During the weak days the daytime winds are stronger with the maximum wind speed varying from 4 to 6 $\mathrm{m\,s^{-1}}$ as compared to active days, when wind speeds were less than 2 $\mathrm{m\,s^{-1}}$. This is believed to be due to stronger mixing in the planetary boundary layer. However, on days 5–7 August, wind speed reached a maximum

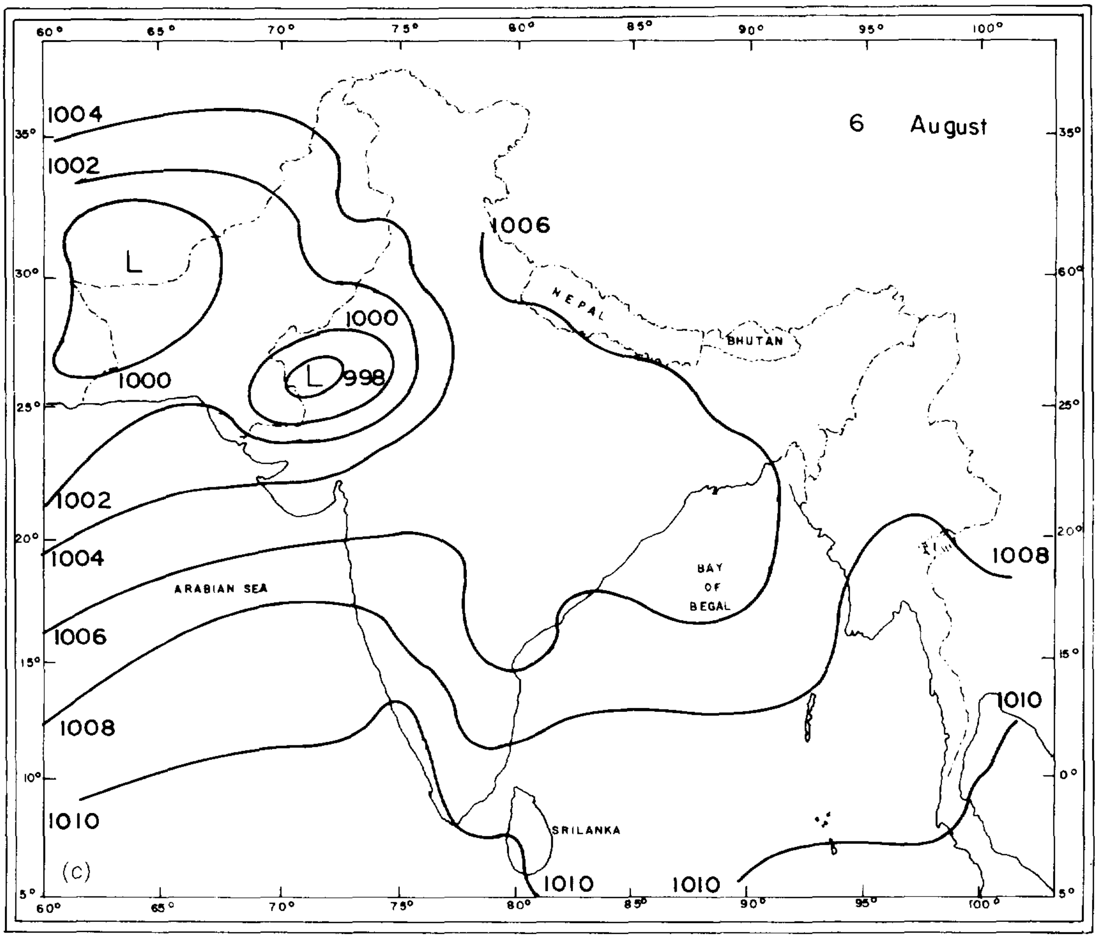

Fig. 2. Surface pressures in mb over the Indian region at 8.30 LST: (a) for 29 July 1990, (b) for 3 August 1990 and (c) for 6 August 1990.

of 8 m s^{-1} because of the presence of a synoptic low pressure system over Rajasthan. Wind variations during weak monsoon days are generally smoother showing a maximum around the noon or afternoon whereas during active days sub-diurnal scales or mesoscale variations in wind speeds are seen.

Diurnal variations in temperatures are shown in Fig. 6a and b for weak and active days, respectively. Maximum air temperature generally occurs between 3 and 4 p.m. and drops from a value of 35°C during weak days to less than 28°C during active days.

Figure 7 shows the diurnal variation in humidity at two levels, namely 1 m and 30 m, respectively, during weak monsoon days. Relative humidity is a maximum around 6 a.m. when the temperatures are lowest, and a minimum around 4 p.m. when the temperatures are highest. Relative humidity varies from a maximum of 80% to a minimum of 50%. During active days relative humidity is generally more than 90%.

Kharagpur. The number of 15 min samples during a day varied from a minimum of one to a maximum of four. A comparison of the diurnal variation in winds (Fig. 8a and b) between active and weak monsoon days indicates no significant difference in either the wind speed or its diurnal variation. On 30 July, the wind speed reached a maximum of 8 m s^{-1}. Diurnal variations in mean air temperature could not be obtained due to the malfunctioning of the instruments. Diurnal variations in humidity at heights 1, 4 and 30 m during weak and active days are shown in Fig. 9. Variations are not significant. Humidity at the lower levels (1 and 4 m) is almost always more than 80%, and at height 30 m, it is more than 50%, on both active and weak days.

4.2. *Roughness length*

To determine the roughness length Z_0, a stability-corrected wind profile method was used. The profile adopted is the relationship proposed by Businger (1973) and Z_0 is calculated as follows.

$$U/u_* = 1/\kappa(\log(Z/Z_0) - \psi(Z/L)) \quad (1)$$

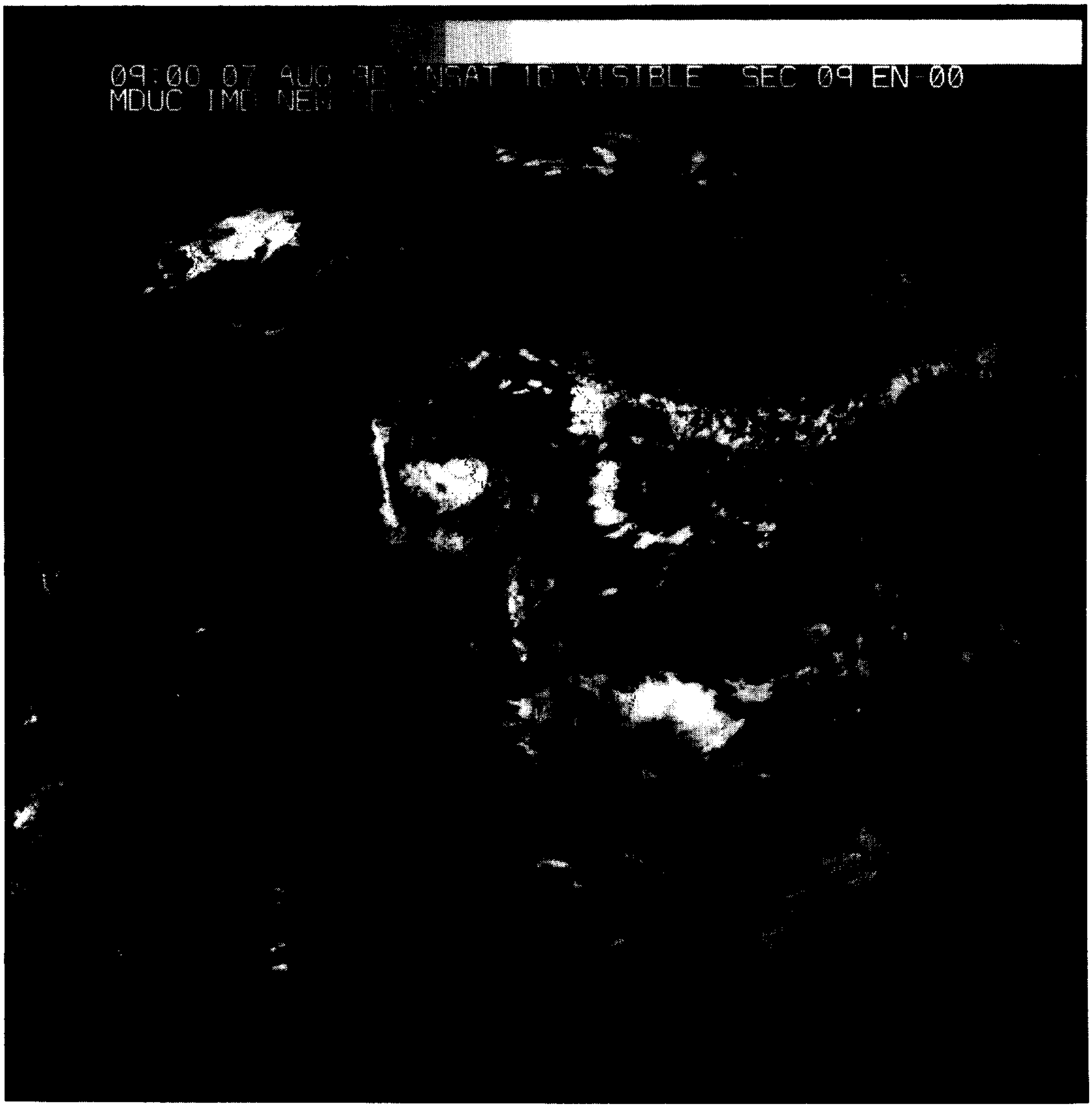

Fig. 3. INSAT-1D visible satellite picture taken at 09 GMT on 7 August 1990.

where

$$\psi(Z/L) = \begin{cases} -4.7\, Z/L & \text{for } Z/L > 0 \text{ (stable)}, \\ 2\log((1+x)/2) + \log((1+x^2)/2) - 2\tan^{-1} x \\ \quad + \pi/2 & \text{for } Z/L < 0 \text{ (unstable)}, \end{cases}$$

$$x \equiv (1 - 15(Z/L))^{1/4}.$$

Using u_* and L obtained from turbulence and flux data, Z_0 was obtained from equation (1). Average values of 12 cm and 2 cm were estimated for Jodhpur and Kharagpur respectively.

4.3. *Surface layer parameters*

Various surface layer variables such as friction velocity, friction temperature, stability parameters and turbulent heat and momentum fluxes are calculated using fast data and are tabulated in Tables 1 and 2 respectively for Jodhpur and Kharagpur. The first column represents the data and time of observations. The second column represents the friction velocity u_* derived from fast data according to the relation

$$u_* = [(\overline{u'w'})^2 + (\overline{v'w'})^2]^{1/4}$$

u_* generally increases with wind speed both at Jodhpur and Kharagpur, u_* shows a minimum when the winds are very low at Jodhpur. The friction temperature calculated as $\theta_* = -(\overline{w'T_v'})/u_*$, is given in column 3.

In column 4 the flux R_{if} is given. The flux Richardson number is obtained from

$$R_{if} = \left(\frac{g}{\bar{\theta}}\right) \frac{\overline{w'T_v'}}{\overline{u'w'}(\partial\bar{u}/\partial z)}.$$

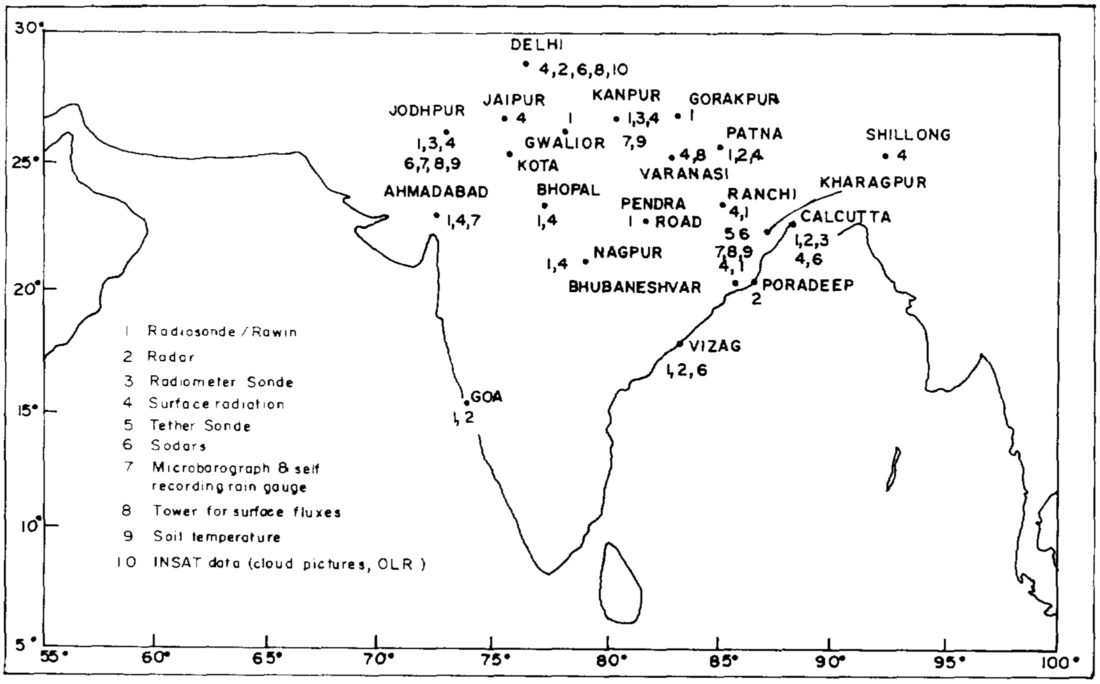

Fig. 4. Monsoon trough boundary layer experiment (MONTBLEX) observations network.

It is seen that the surface layer is generally near neutral or moderately unstable (− 0.5– −0.1).

Column 8 lists the stability parameter Z/L. We note that again, Z/L and Richardson numbers represent the same stability situation. In columns 9 and 10 are given the turbulent fluxes of heat $(\overline{w'T'_v})$ and momentum $(\overline{U'w'})$. A discussion of these fluxes is presented in the next section.

4.4. *Turbulent fluxes of heat and momentum*

The turbulent fluxes of heat, $(\rho c_p \overline{w'T'_v})$ and momentum $(-\rho\overline{U'w'})$ are calculated by the eddy correlation method using the fast data obtained by the sonic anemometers. By calculating the fluctuating components u', v', w' and T'_v from the observed time series data of horizontal velocities, vertical velocity and virtual temperature recorded at 8 Hz, and computing the covariances, the surface fluxes of momentum and heat are estimated. Here the time averages are over periods of 15 min. The diurnal variation of these fluxes is shown in Figs 10 and 11 for the period from 26 July to 10 August at both Jodhpur and Kharagpur. Figure 10a–c shows the momentum flux at Jodhpur for the weak and the active days, and Fig. 10d–f that at Kharagpur for the same days. At Jodhpur, the momentum flux is significantly large on 5 and 6 August, when it is more than 0.5 N m^{-2}, because the winds were stronger on these days due to a low located over the Rajasthan region (Fig. 5b). Otherwise the fluxes are larger during weak monsoon days, being of magnitude around 0.2 N m^{-2}, as compared to the active days (0.1 N m^{-2}) because the winds are stronger during weak monsoon days. At Kharagpur, Fig. 10d–f, the momentum flux is about 0.1 N m^{-2}, and there is no significant difference between weak and active monsoon days. There could be several reasons for this phenomenon. Prolonged soil wetness, copious rainfall and lack of horizontal gradients in soil moisture are some of the possible causes.

The turbulent heat fluxes at Jodhpur for the weak and active monsoon days are shown in Fig. 11a–c, and at Kharagpur in Fig. 11d–f. As expected, the heat flux at Jodhpur is large during weak monsoon days, the maximum being 450 W m^{-2} on 30 July, whereas during active days it never exceeded 160 W m^{-2}. At Kharagpur (Fig. 11d–f), the heat flux does not vary significantly between active and weak monsoon days, the maximum in either phase being 150 W m^{-2}.

Heat fluxes averaged during the daytimes and the distribution of rainfall for the weak and the active periods are shown in Fig. 12a and b, respectively for Jodhpur and Kharagpur. The daytime averaged heat fluxes were obtained by averaging the heat fluxes at different times between 8 a.m. and 5 p.m. As seen earlier, the heat fluxes at Jodhpur are larger during weak monsoon days than on active days. There was no rainfall at Jodhpur on weak monsoon days and the heat flux is then relatively large (about 250 W m^{-2}) on all weak days from 26 July to 1 August. During some active days, the maximum rainfall exceeded 5 cm whereas the heat flux never exceeded 100 W m^{-2}. At Kharagpur (Fig. 12b), there is no significant variation in turbulent heat fluxes between active and weak

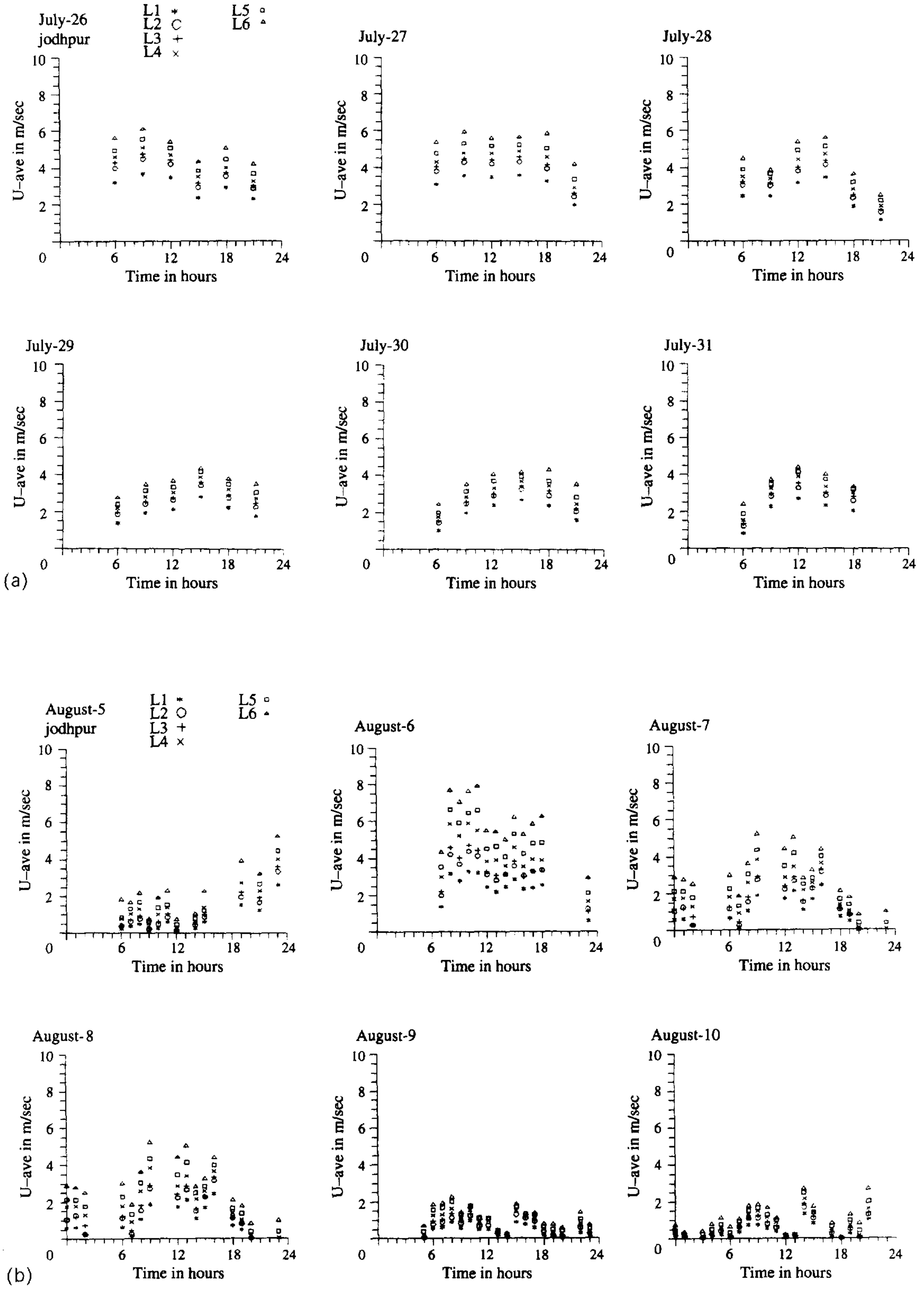

Fig. 5. Diurnal variation of mean winds at Jodhpur: (a) during weak monsoon days (26–31 July); (b) during active days (5–10 August).

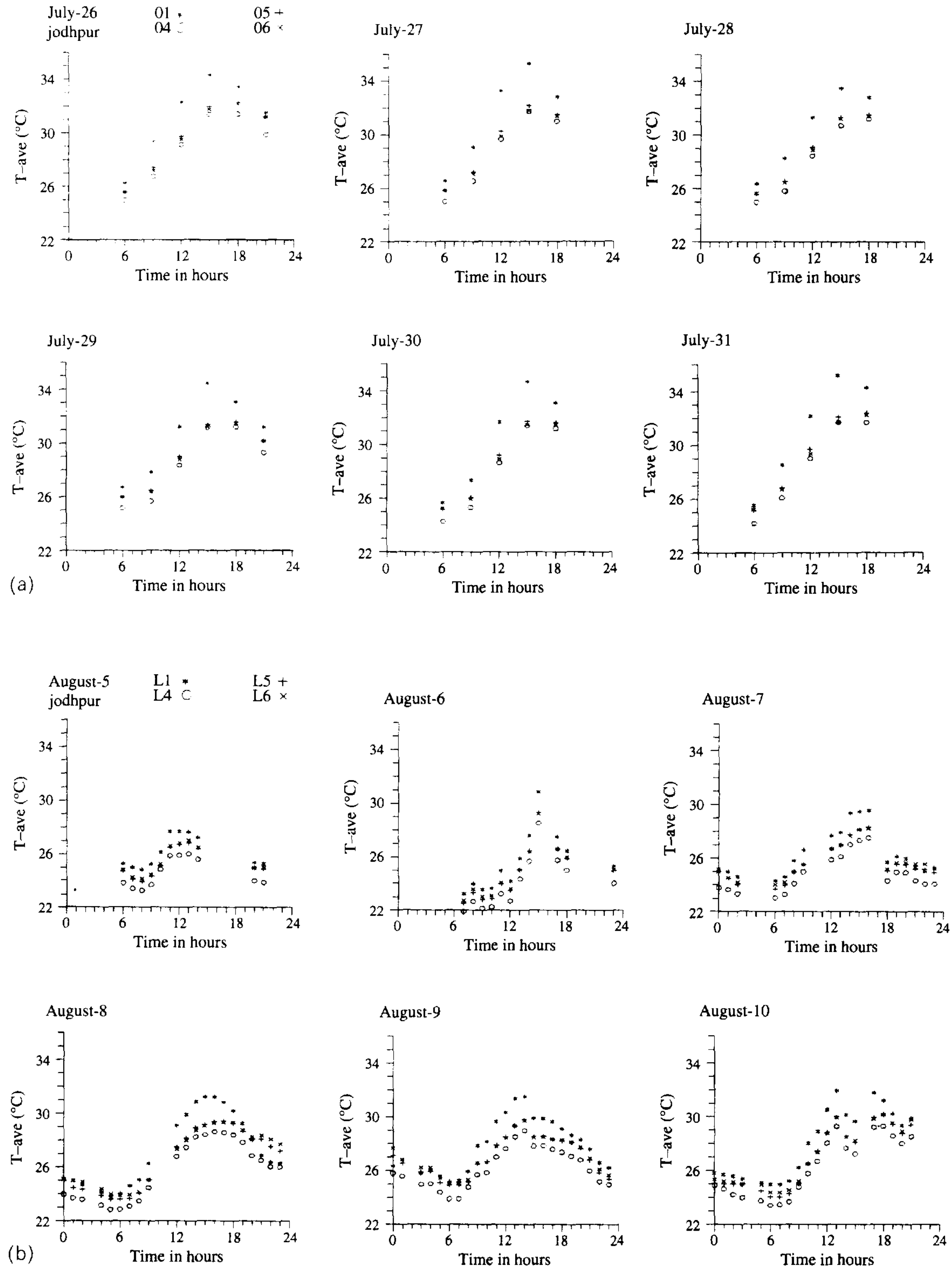

Fig. 6. Diurnal variation of mean temperatures at Jodhpur: (a) during weak monsoon days (26–31 July); (b) during active days (5–10 August).

monsoon days. However, the maximum rainfall exceeded 7 cm during weak monsoon days and was negligible on most of the active days. The rainfall at Kharagpur (Fig. 12b) shows a reversal in the pattern of the rainfall at Jodhpur, during weak and active days. Thus the active phase of the monsoon is not uniform over the subcontinent.

One question that arises is whether the soil moisture and insolation play an indirect but significant role in the generation of turbulent heat fluxes by regula-

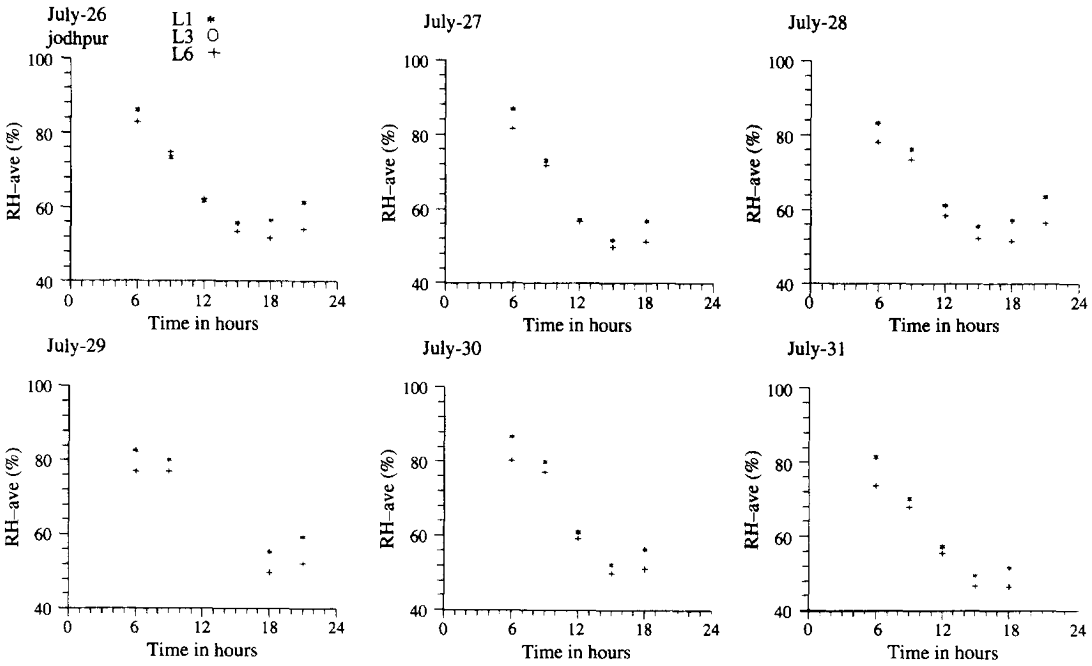

Fig. 7. Diurnal variation of mean relative humidity during weak monsoon days (26–31 July) at Jodhpur.

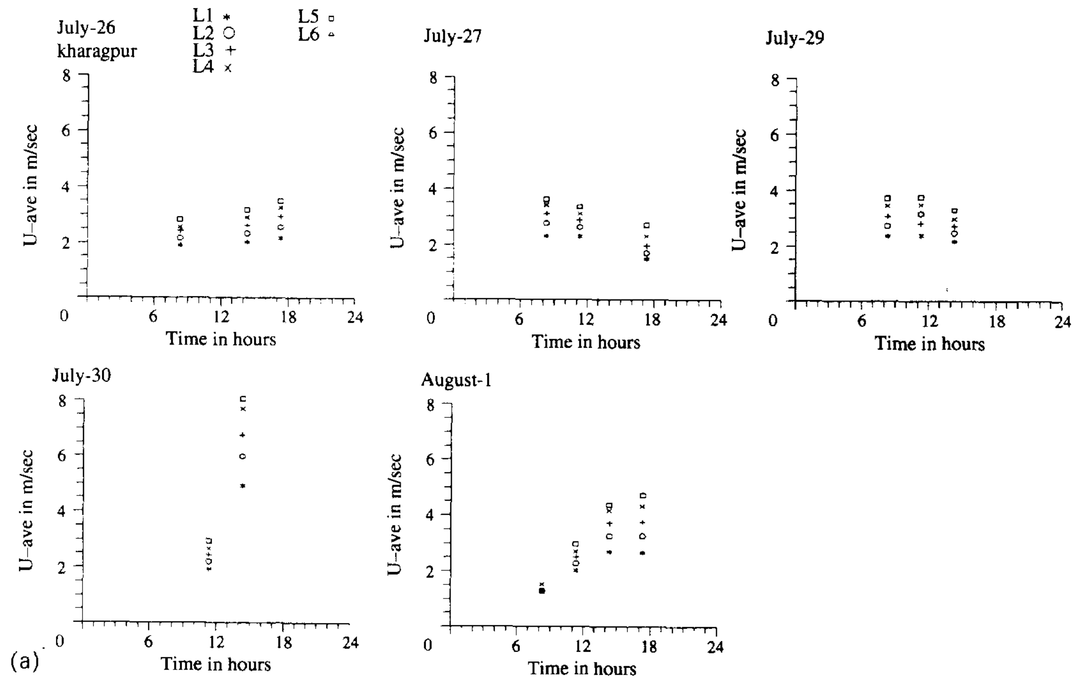

Fig. 8a.

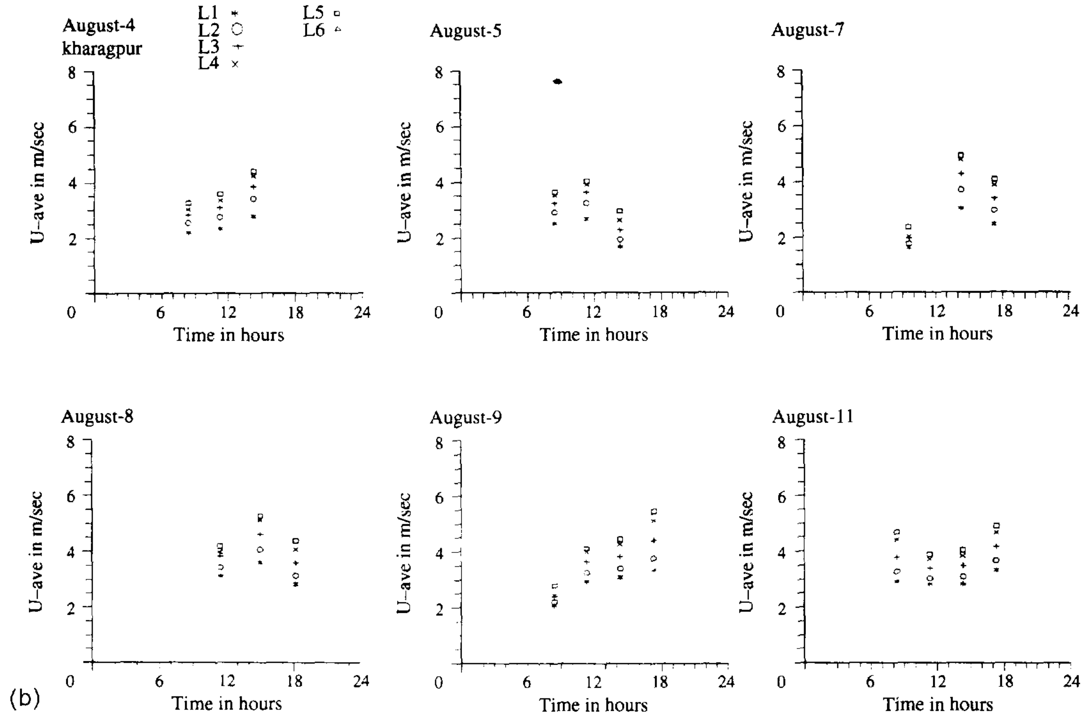

Fig. 8. Diurnal variation of mean winds at Kharagpur: (a) during weak monsoon days (26–31 July, 1 August); (b) during active days (4–11 August).

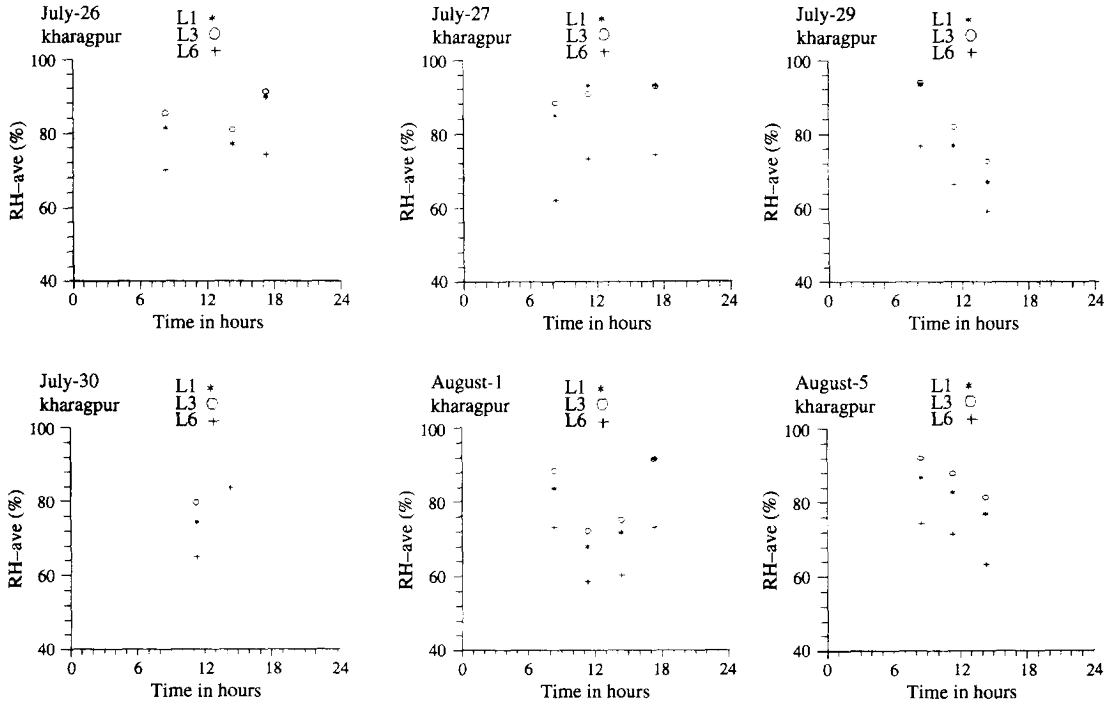

Fig. 9

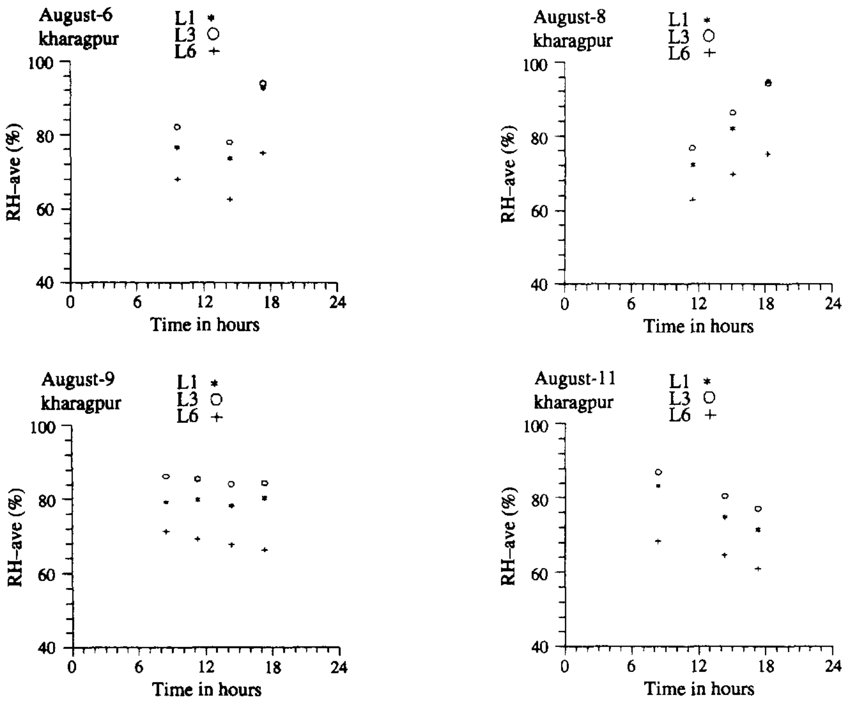

Fig. 9. Diurnal variation of mean relative humidities during weak and active monsoon days at Kharagpur.

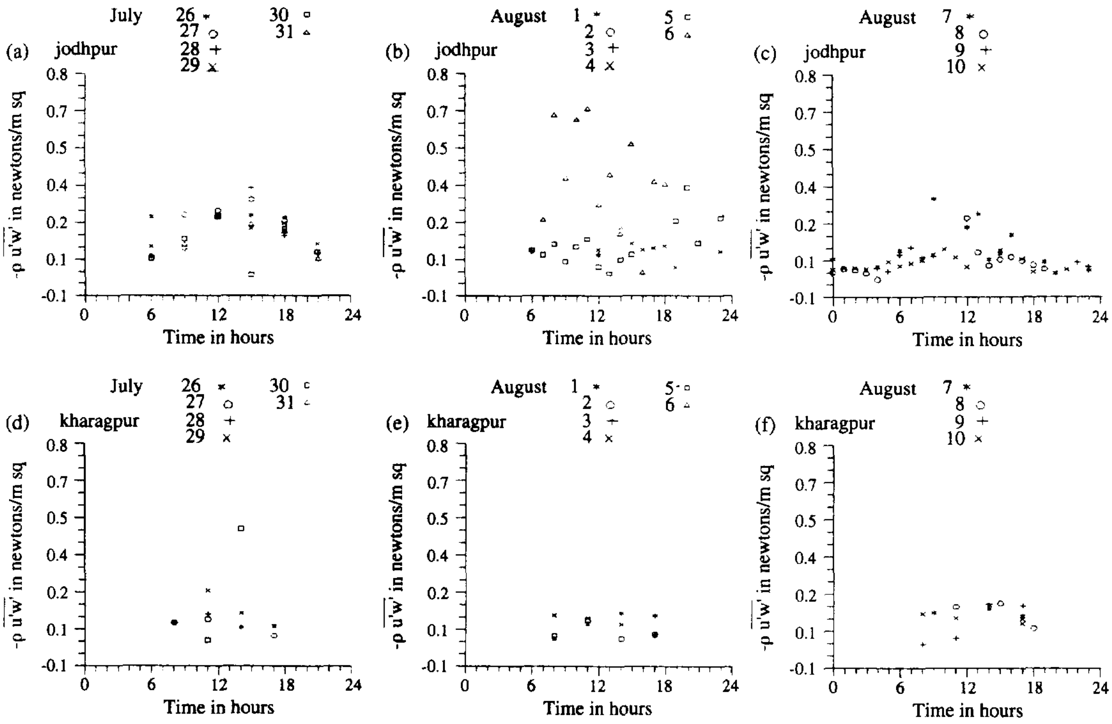

Fig. 10. Diurnal variation of turbulent momentum flux, $\rho \overline{U'w'}$ in N m^{-2} during active and weak monsoon days at Jodhpur and Kharagpur.

Table 1. Typical surface layer parameters for the weak (26 July–1 August) and active (2–10 August) monsoon periods at Jodhpur

Date		Time	u_* (m s^{-1})	t_* (°C)	R_{if}	L (m)	Z/L	$\overline{w't'}$ (m s^{-1} °C)	$\overline{u'w'}$ (m s^{-2})
July	26	0600	0.43	−0.01	−0.01	−1212.5	−0.00	0.005	−0.185
	26	1200	0.44	−0.47	−0.40	−32.1	−0.12	0.206	−0.193
	26	1500	0.44	−0.30	−0.23	−51.2	−0.08	0.130	−0.189
	26	1800	0.43	−0.03	−0.03	−413.5	−0.01	0.015	−0.184
	27	0900	0.45	−0.23	−0.21	−67.3	−0.06	0.104	−0.192
	27	1200	0.46	−0.68	−0.52	−24.3	−0.16	0.311	−0.205
	27	1500	0.49	−0.61	−0.40	−30.6	−0.13	0.301	−0.243
	27	1800	0.44	−0.11	−0.09	−135.3	−0.03	0.049	−0.169
	29	0600	0.29	0.01	0.03	465.6	0.01	−0.004	−0.084
	29	0900	0.31	−0.17	−0.37	−42.2	−0.09	0.054	−0.071
	29	1500	0.38	−0.62	−0.67	−18.1	−0.22	0.236	−0.145
	29	1800	0.42	−0.15	−0.16	−94.6	−0.04	0.061	−0.163
	29	2100	0.31	0.04	0.06	177.5	0.02	−0.013	−0.094
	30	0600	0.22	0.05	0.15	73.7	0.05	−0.011	−0.046
	30	0900	0.34	−0.15	−0.26	−57.8	−0.07	0.052	−0.110
	30	1200	0.44	−0.51	−0.54	−29.3	−0.14	0.225	−0.189
	30	1800	0.38	−0.11	−0.11	−104.3	−0.04	0.041	−0.143
August	06	0700	0.42	−0.01	−0.00	−1398.0	−0.00	0.004	−0.176
	06	0800	0.73	0.00	0.00	14719.3	0.00	−0.002	−0.527
	06	0900	0.56	−0.02	−0.00	−1474.4	−0.00	0.009	−0.316
	06	1000	0.72	−0.02	−0.00	−2564.3	−0.00	0.011	−0.511
	06	1100	0.75	−0.04	−0.01	−1143.3	−0.00	0.028	−0.549
	06	1300	0.58	−0.09	−0.03	−291.3	−0.01	0.051	−0.328
	06	1400	0.43	−0.12	−0.16	−119.3	−0.03	0.051	−0.128
	06	1500	0.67	−0.21	−0.06	−164.9	−0.02	0.141	−0.429
	06	1700	0.57	−0.05	−0.03	−472.5	−0.01	0.030	−0.305
	06	1800	0.56	0.01	0.01	1675.4	0.00	−0.008	−0.296
	07	0000	0.30	0.03	0.06	205.3	0.02	−0.010	−0.046
	07	0600	0.32	0.04	0.05	206.9	0.02	−0.012	−0.075
	07	0900	0.60	−0.10	−0.04	−279.3	−0.01	0.059	−0.249
	07	1200	0.41	−0.06	−0.05	−203.0	−0.02	0.026	−0.153
	07	1300	0.47	−0.03	−0.02	−568.4	−0.01	0.014	−0.199
	07	1400	0.33	−0.28	−0.62	−30.1	−0.13	0.092	−0.045
	07	1500	0.29	−0.16	−0.46	−41.7	−0.10	0.045	−0.064
	07	1600	0.38	−0.13	−0.15	−86.3	−0.05	0.049	−0.128
	07	1900	0.20	0.04	0.17	87.1	0.05	−0.007	−0.036
	07	2000	0.13	0.04	−2.83	33.5	0.12	−0.005	0.003
	09	0600	0.25	0.02	0.04	198.0	0.02	−0.006	−0.061
	09	0700	0.29	−0.01	−0.02	−618.3	−0.01	0.003	−0.086
	09	0800	0.23	−0.05	−0.09	−84.2	−0.05	0.011	−0.051
	09	0900	0.24	−0.20	−0.56	−22.1	−0.18	0.048	−0.056
	09	2200	0.19	0.01	0.04	261.8	0.02	−0.002	−0.033
	09	2300	0.16	−0.01	−0.11	−312.2	−0.01	0.001	−0.019
	10	0100	0.16	−0.01	−0.36	−155.9	−0.03	0.002	−0.017
	10	0600	0.15	0.01	0.07	256.2	0.02	−0.001	−0.023
	10	0700	0.18	−0.02	−0.13	−110.7	−0.04	0.004	−0.032
	10	0800	0.20	−0.09	−0.40	−35.7	−0.11	0.017	−0.041
	10	0900	0.24	−0.15	−0.31	−29.3	−0.14	0.036	−0.060
	10	1000	0.29	−0.28	−0.51	−23.1	−0.17	0.081	−0.080
	10	1100	0.24	−0.18	−0.53	−24.1	−0.17	0.044	−0.053
	10	1500	0.27	−0.34	−0.67	−16.3	−0.25	0.093	−0.075
	10	1700	0.22	−0.25	−0.95	−15.3	−0.26	0.054	−0.045
	10	2100	0.10	0.06	0.34	12.9	0.31	−0.006	−0.011

Units: MKS.

ting the ground temperature. This question can be addressed by considering soil and air temperatures with reference to cloud cover. Daily variations of maximum air temperature at 1 m, daily maximum soil temperature at 10 cm below the ground level and the relative humidity are given in Fig. 13. At Jodhpur, both air and soil temperatures are larger during weak monsoon days. Relative humidity during weak monsoon days for Jodhpur is around 20 to 30%. It reaches a maximum of about 95% during active days.

The soil temperature at 10 cm is less during active days as compared to the weak monsoon days possibly

Table 2. Typical surface layer parameters for the weak (26 July–1 August) and active (2–10 August) monsoon periods at Kharagpur

Date		Time	u_* (m s^{-1})	t_* (°C)	R_{if}	L (m)	Z/L	$\overline{w't'}$ (m s^{-1} °C)	$\overline{u'w'}$ (m s^{-2})
July	26	0831	0.26	− 0.10	− 0.38	− 50.2	− 0.16	0.027	− 0.064
	26	1430	0.23	− 0.07	− 0.23	− 55.4	− 0.14	0.017	− 0.049
	26	1730	0.23	− 0.05	− 0.14	− 78.4	− 0.10	0.012	− 0.053
	27	0830	0.26	− 0.13	− 0.35	− 41.1	− 0.19	0.033	− 0.065
	27	1130	0.28	− 0.26	− 0.71	− 23.6	− 0.34	0.072	− 0.076
	27	1730	0.15	0.04	0.14	43.3	0.18	− 0.006	− 0.020
	28	1130	0.32	− 0.46	− 0.91	− 17.4	− 0.46	0.146	− 0.092
	29	0830	0.26	− 0.12	− 0.28	− 42.2	− 0.19	0.032	− 0.065
	29	1130	0.42	− 0.20	− 0.19	− 66.6	− 0.12	0.086	− 0.173
	29	1430	0.34	− 0.18	− 0.40	− 50.0	− 0.16	0.061	− 0.095
	30	1430	0.63	− 0.06	− 0.03	− 491.1	− 0.02	0.039	− 0.380
August	01	1133	0.26	− 0.28	− 0.91	− 18.7	− 0.43	0.073	− 0.062
	01	1434	0.32	− 0.17	− 0.30	− 47.3	− 0.17	0.054	− 0.098
	01	1730	0.30	0.03	0.04	232.4	0.03	− 0.009	− 0.089
	02	1430	0.35	− 0.25	− 0.43	− 37.6	− 0.21	0.088	− 0.119
	04	0843	0.30	− 0.35	− 0.92	− 19.9	− 0.40	0.105	− 0.090
	04	1130	0.29	− 0.34	− 0.87	− 19.1	− 0.42	0.099	− 0.082
	04	1430	0.26	− 0.22	− 0.60	− 23.6	− 0.34	0.058	− 0.060
	05	0845	0.14	− 0.40	− 2.55	− 3.8	− 2.12	0.056	− 0.019
	05	1130	0.27	− 0.20	− 0.67	− 27.8	− 0.29	0.055	− 0.073
	05	1730	0.11	0.05	0.21	20.7	0.39	− 0.005	− 0.012
	07	0958	0.32	− 0.50	− 1.38	− 15.9	− 0.50	0.159	− 0.104
	07	1430	0.34	− 0.23	− 0.35	− 39.5	− 0.20	0.077	− 0.118
	07	1730	0.31	− 0.02	− 0.03	− 458.5	− 0.02	0.005	− 0.094
	08	1145	0.36	− 0.36	− 1.07	− 27.8	− 0.29	0.130	− 0.124
	08	1504	0.37	− 0.09	− 0.14	− 111.6	− 0.07	0.035	− 0.137
	08	1824	0.23	0.03	0.06	133.9	0.06	− 0.007	− 0.052
	09	1130	0.26	− 0.40	− 4.14	− 12.9	− 0.62	0.105	− 0.019
	09	1430	0.38	− 0.37	− 0.59	− 30.4	− 0.26	0.140	− 0.135
	09	1730	0.36	0.01	0.01	902.4	0.01	− 0.004	− 0.130
	10	1730	0.26	− 0.00	− 0.01	− 1362.2	− 0.01	0.001	− 0.068
	11	0830	0.32	− 0.12	− 0.26	− 68.3	− 0.12	0.037	− 0.101
	11	1131	0.29	− 0.36	− 0.74	− 18.4	− 0.44	0.103	− 0.086
	11	1431	0.37	− 0.15	− 0.19	− 73.0	− 0.11	0.054	− 0.131
	11	1730	0.29	0.01	0.02	473.1	0.02	− 0.004	− 0.083

Units: MKS.

due to increased soil moisture. There was no ground temperature measurement made during this period. We have used air temperature variation at 1 m as an indirect indicator of the variation of the ground temperature. Near surface air temperatures are higher on all weak monsoon days than on active days. The reason is probably the strong evaporative cooling associated with higher soil moisture content during active days. There appears to be good correspondence between near surface (1 m) air temperature and the turbulent heat flux. One other variable that can influence surface heat flux is the cloud cover.

Cloud amount in oktas observed at 17.30 LST (Fig. 13b) indicates no significant variation between weak and active monsoon days although cloud type varied appreciably. Weak monsoon days were associated with stratocumulus type of clouds and the active with cumulonimbus. A comparison of Figs 12a and 13b suggests that there is no correlation between the turbulent heat flux and the cloud cover. In other words, the variation of air temperature at 1 m between active and weak monsoon situations is not explained by cloud cover variation.

Hence it appears that the soil moisture is an important factor in determining the near-surface air temperatures between weak and active monsoon days. This effect could not be tested at Kharagpur due to lack of surface temperatures. However, an interesting feature is apparent from Figs 12b and 13b. Although rainfall was negligible beyond 3 August, surface turbulent heat flux did not increase immediately probably because of the ground wetness. It took about seven days for the heat flux to increase appreciably.

5. CONCLUSIONS

Mean structure of the atmospheric surface layer is found to be different at Jodhpur (arid region) and Kharagpur (moist region), both located along the

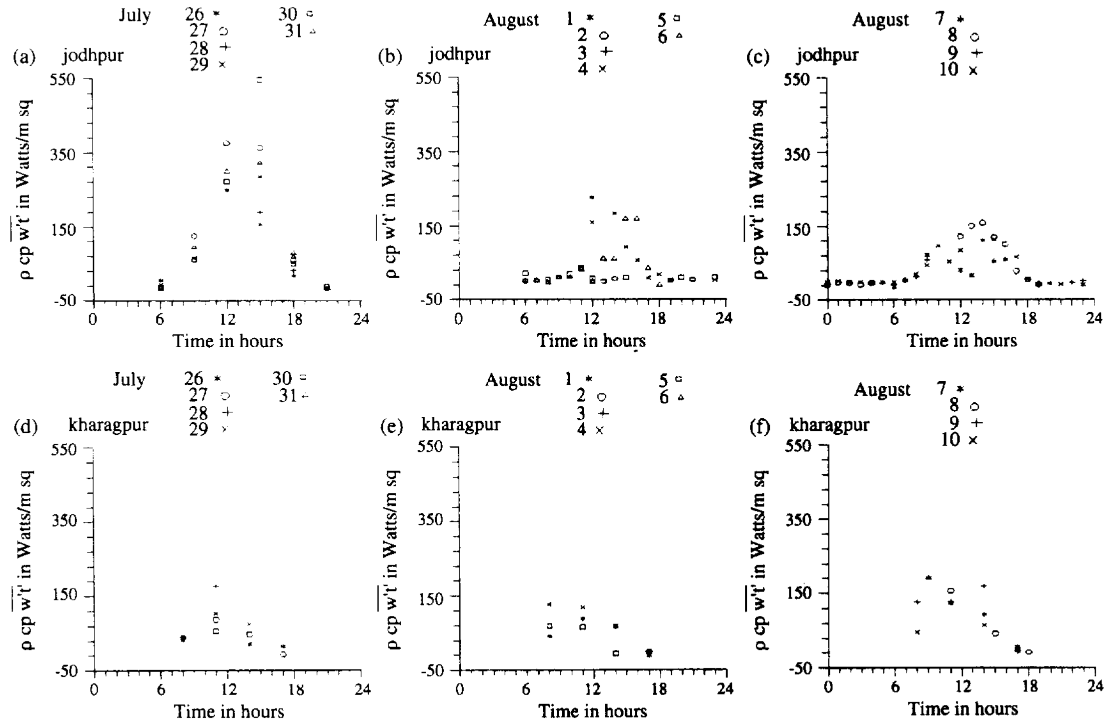

Fig. 11. Diurnal variation of turbulent heat flux, $\rho c_p \overline{w'T'_v}$ in W m^{-2} during active and weak monsoon days at Jodhpur and Kharagpur.

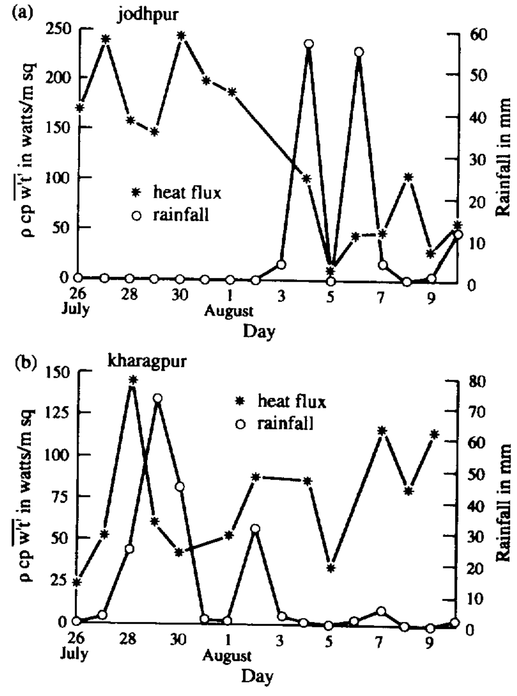

Fig. 12. Daytime averaged turbulent heat fluxes in W m^{-2} and rainfall in mm for weak and active monsoon days at (a) Jodhpur and (b) Kharagpur.

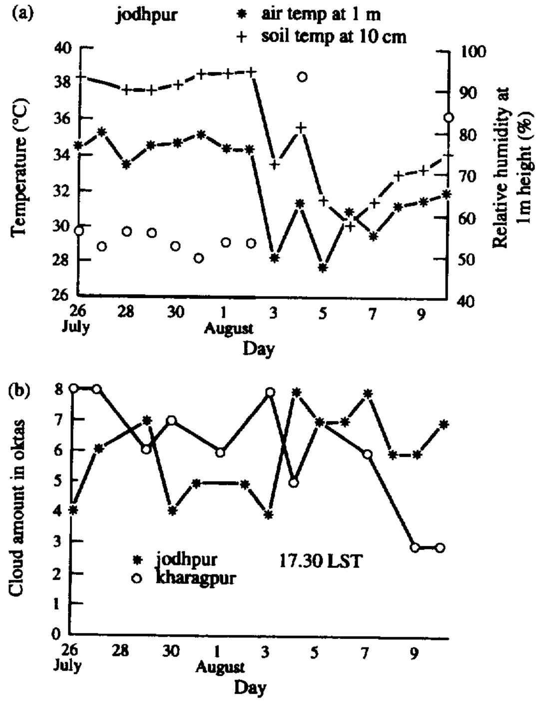

Fig. 13. (a) Maximum air temperature at 1 m, maximum soil temperature at 10 cm below the ground level and relative humidity at 1 m during weak and active monsoon days at Jodhpur. (b) Amount of cloudiness in oktas observed at 17.30 LST during weak and active monsoon days at Jodhpur.

monsoon trough for active and weak monsoon periods. At Jodhpur, winds are stronger during weak monsoon days as compared to the active days; whereas at Kharagpur there is no significant difference between the two periods. Increase in wind speed at Jodhpur during weak monsoon period is believed to be due to stronger mixing. In Jodhpur, active monsoon days are characterised by temporal changes that last for about two hours possibly due to mesoscale convection. The turbulent heat flux was larger at Jodhpur during weak monsoon days as compared to active days. No significant variation was found at Kharagpur. Indirect evidence suggests that the soil moisture may be an important factor in regulating the ground temperature and hence the surface turbulent heat flux. In this study cloud cover does not seem to be a factor in the variation of the surface heat flux.

Acknowledgements—The authors thank S. Rudra Kumar, K. Narahari Rao and H. P. Srinivasan for helpful interaction. The authors thank Mrs R. Rama for her patient help in wordprocessing the manuscript. Partial support for this work was provided by the Division of International Programs, National Science Foundation under grants INT 92-16253 and INT 93-00751.

REFERENCES

Businger J. A. (1973) Turbulent transfer in the atmospheric surface layer. Workshop on Micrometeorology (edited by Haugen D. A.). American Meteorological Society, Boston, Massachusetts, pp. 67–100.

Goel M. and Srivastava H. N. (1990) Monsoon trough boundary layer experiment (MONTBLEX). *Bull. Am. Met. Soc.* **71,** 1594–1600.

Kaimal J. C. (1988) The atmospheric boundary layer — its structure. Lecture Notes, IITM Visiting Professorship Program.

Kaimal J. C. (1989) Minimizing flow distortion errors. In Proc. 5th European Physical Society, Liquid State Conference, Moscow, 16–20 October.

Krishnamurti T. N. and Subrahmanayam D. (1982) The 30–50 day mode at 850 mb during MONEX. *J. atmos. Sci.* **39,** 2088–2095.

Kusuma G. Rao (1986) Sensible heat fluxes during the active and break phases of the southwest monsoon over the Indian region. *Boundary-Layer Met.* **36,** 283–294.

Kusuma G. Rao, Sethuraman and Prabhu A. (1991) Boundary layer heights over the monsoon trough region during active and break phases. *Boundary-Layer Met.* **57,** 129–138.

Kusuma G. Rao and Prabhu A. (1992) Computations of sensible heat and momentum fluxes using fast data for Jodhpur during 1–12 July 1990. IISc Report 92 AS 5. IISc., Bangalore.

Parasnis S. S. (1991) The convective boundary layer during active and break conditions of summer monsoon. *J. atmos. Sci.* **48**(7), 999–1002.

Prabhu A., Narahari Rao K., Kusuma G. Rao, Sudarsh V. Kailas, Rudra Kumar S., Ameenulla S. and Srinivasan H. P. (1990) MONTBLEX pilot experiment, 1989 — Tower Component, IISc Report 90 AS 2. IISc., Bangalore.

Raman S., Templeman B., Templeman S., Holt T., Murthy A. B., Singh M. P., Agarwal P., Nigam S., Prabhu A. and Ameenulla S. (1990) Structure of the Indian southwesterly pre-monsoon and monsoon boundary layers. Observations and Numerical Simulation. *Atmospheric Environment* **24A**(4), pp. 723–734.

Ramaswamy C. (1973) A normal period of large scale break in the southwest monsoon over India. *Current Science* **42**(15), 517–523.

Rao Y. P. (1976) Southwest monsoon. *Meteor. Monogr.* 1/1976, India Meteorological Department, pp. 367.

Rudra Kumar S. and Prabhu A. (1992) Surface layer observations under the programme MONTBLEX. IISc Report 92 AS 2. IISc., Bangalore.

Saltzman B. and Ashe S. (1976) Parameterization of the monthly mean vertical heat transfer at the Earth's surface. *Tellus* **28,** 323–331.

Sivaramakrishnan S., Sangeetha Sexena and Vernekar K. G. (1992) Characteristics of turbulent fluxes of sensible heat and momentum in the surface boundary layer during the Indian summer monsoon. *Boundary-Layer Met.* **60,** 95–108.

Yasunari T. (1979) Cloudiness fluctuations associated with the northern hemisphere summer monsoon. *J. Meteor. Soc. Japan*, **57,** 227–242.