Journal of Agrometeorology 3 (1&2) : 107 -117 (June-December 2001)

Characteristics of momentum and sensible heat flux during the monsoon conditions over LASPEX-97 region

M. N. PATIL, B. S. MURTHY AND S. S. PARASNIS
Indian Institute of Tropical Meteorology, Pashan, Pune - 411008

ABSTRACT

The data on wind and temperature collected during Land Surface Processes Experiment (LASPEX-97) for the month of July and September 1997 were used to study the fluxes of sensible heat and momentum. The analysis suggested that the sensible heat flux was maximum of the order of 100 Wm^{-2} between 1300-1500 hrs (IST) at all stations of LASPEX-97. Maximum momentum flux was observed at about 1600 hrs (IST). Drag (C_D) and heat exchange (C_H) coefficient decreased with increasing stability (z/L). C_D and C_H showed higher magnitude in September than those in July. C_H was 2-3 times greater than C_D.

Key words : Sensible heat flux, Momentum flux, Net radiation, Exchange coefficients.

Over the past decade, it has become apparent that the numerical weather prediction and general circulation models require a more accurate representation of the complex interactions occurring at the land surface in terms of the exchanges of surface fluxes of heat, momentum and moisture. These fluxes can be estimated using bulk aerodynamic method in which exchange coefficients are used. Exchange coefficients vary with different atmospheric parameters over land such as roughness length, wind speed, stability etc. The information on these coefficients are essential to modify the surface conditions which are to be incorporated in the numerical weather prediction and climate forecasting models to provide better simulations.

Garratt (1977) has reported a comprehensive review on C_D over land as well as sea surface. The variation of C_D and C_H with wind speed and stability are described elsewhere Stull (1988). Using the Monsoon Trough Boundary Layer Experiment (MONTBLEX) data, some attempts were made to provide the information on the fluxes and C_D by various worker (Patil and Parasnis, 2001; Kusuma, 1996; Mohanty *et.al.*, 1995) and on C_H (Patil and Parasnis, 2001; Kusuma *et.al.*, 1996). The Land Surface Processes Experiment (LASPEX-97) provided on-site observations where soil properties, agriculture practice and climatic conditions change drastically from station to station. The purpose here is to investigate the characteristics of the surface fluxes of sensible heat and momentum with respect to different soil and vegetation properties.

MATERIALS AND METHODS

LASPEX-97 was carried out in the state of Gujarat in the Mahi and Sabarmati river basin where large climate variability as well as soil properties persist. Qualitative details of the experiment can be found in this issue (Shekh *et.al.*, 2001).

Data analysis

The data collected at the site was supplied to the users at 1 minute interval. For the analysis in the present work, it was further averaged for 1 hour. According to the Monin-Obukhov similarity theory (Businger *et. al.*, 1971; Yaglom, 1977; McBean, 1979), the vertical profiles of wind and temperature for turbulent flow in the surface layer can be described by the following equations:

$$u(z) = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \Psi_H\left(\frac{z}{L}\right) + \Psi_M\left(\frac{z_0}{L}\right)\right] \qquad \text{--- (1)}$$

$$\Delta\theta = \theta(z_2) - \theta(z_1);$$

$$= \frac{\theta_*}{k}\left[\ln\left(\frac{z_2}{z_1}\right) - \Psi_H\left(\frac{z_2}{L}\right) + \Psi_H\left(\frac{z_1}{L}\right)\right] \qquad \text{---(2)}$$

where u_* is the friction velocity defined by

$u_*^2 = \tau / \rho$

where τ is wind stress and θ is density of air; z_0 is the surface roughness length; $k=0.4$ is the von Karman constant; θ_* is the flux temperature scale; ψ_M, and ψ_H are the stability function for momentum and sensible heat flux respectively;

$L = u_*T/kg\theta_*$

is the Obukhov length;

$T = [\theta(z_1)+\theta(z_2)]/2;$

and g is the acceleration due to gravity. The momentum flux (τ) and sensible heat flux (H) were estimated by the following equations

$$\tau = \rho u_*^2 \qquad \text{--- (3)}$$

$$H = -\rho C_p u_* \theta_* \qquad \text{--- (4)}$$

Different form of stability functions have been derived and used in the literature. According to recent review of Hogstrom (1988), the early formulations obtained by Paulson (1970), Dyer and Hick (1970) and Hicks (1976) are still good approximations for an unstable surface layer and were used in the analysis for the case of unstable stratification ($\theta_*<0$ or $L < 0$). These formulations are:

$$\Psi_M = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}(x) + \frac{\pi}{2} \qquad (5)$$

$$\Psi_H = 2\ln\left(\frac{1+x^2}{2}\right) \qquad \text{---(6)}$$

where

$$x = \left(\frac{1-16z}{L}\right)^{1/4} = \left(\frac{16\,z\,k\,g\,\theta_*}{T u_*^2}\right)^{1/4}$$

For the case of stable or very stable stratification ($\theta_* >0$ or $L>0$), the following stability functions suggested by Holtslag and DeBruin (1988) and Beljaars and Holtslag (1991) were used.

$$-\Psi_M = a\frac{z}{L} + b\left(\frac{z}{L} - \frac{c}{d}\right)\exp\left(-d\frac{z}{L}\right) + \frac{bc}{d} \qquad \text{--- (7)}$$

$$-\Psi_H = \left(1 + \frac{2\,az}{3\,L}\right)^{3/2} + b\left(\frac{z}{L} - \frac{c}{d}\right)\exp\left(-d\frac{z}{L}\right) + \frac{bc}{d} - 1 \qquad \text{--- (8)}$$

where $a = 1$, $b = 0.667$, $c = 5$ and $d = 0.35$. For estimating u_* and θ_* from equation (1) and (2), iterative procedure was followed.

This is the profile method (Nieuwstadt, 1978; McBean, 1979). Thus the fluxes estimated by (3) and (4) were used to compute the C_D and C_H using following relations.

$$\tau = \rho\, C_D\, u^2 \qquad \text{--- (9)}$$

$$H = -\,\rho\, C_H\, \Delta\theta u \qquad \text{--- (10)}$$

where u is the $[u(z_2)+u(z_1)]/2$. $\Delta\theta$ is the potential temperature difference between z_1 and z_2 level. In the computation, averaged (hourly) wind and temperature data were used at z_1=1 m and z_2=8 m levels.

RESULTS AND DISCUSSION

Estimation of sensible heat and momentum flux were made for the days of Intensive Observational Period (IOP) of the month July and September. IOP was selected from dates 13-18 of each month. The fluxes were averaged on hourly basis over a period of no of days in IOP in a representative month. In this averaging process, we eliminated those values which showed greater spike with respect to the majority of data points. The data used in the study pertains to monsoon season (July) and its withdrawal (September) periods. The sky conditions were cloudy in the region with variable cloud amounts. Cloud conditions for the month of July and September of 1997 are given in Table 1.

Diurnal variation of sensible heat and momentum flux

Fig. 1 shows the diurnal variation of sensible heat flux for the months of July and September over all the stations of LASPEX-97. Maximum sensible heat flux observed at all the stations (except at Arnej in July) was about 100 Wm^{-2}. The variation of fluxes at Sanand in September could not be estimated because of the failure of data recording of some parameters. At Arnej, in July, sensible heat flux remained constant throughout the daytime without displaying routine diurnal cycle. This may be because of water logging at the tower site and the soil was totally moist. However in September, observations showed their natural diurnal cycle. Sensible heat flux maxima were observed at 1300-1500 hrs IST. Maximum momentum flux was observed at 1600 hr IST (Fig. 2) that was 2-3 hours after the peak of sensible heat flux occurred.

The highest value of momentum flux observed at Khandha in July was 0.37 m^2s^{-2}. The stability parameter (z/L) was under near neutral conditions during most of the time except at dawn hrs. Momentum flux was lower in September besides z/L shows higher range of instability during daytime. Wind direction in July was southwest, and in the field, tall crops like sugar cane, pigeon pea were grown. In September, wind direction changed to northwest, where short crops were grown. Thus the influence of vegetation/roughness length was the dominating factors over stability in rising momentum flux at Khandha. Over the LASPEX site, low momentum flux was observed at Anand and Derol in which during daytime, surface layer showed moderate convective instability and stable to near neutral conditions during nighttime. Thus the higher magnitude of fluxes were associated with stronger instability and vice-versa. A comparison of fluxes with different types of soil showed that, higher magnitudes of fluxes were observed over clay soils; where as they were at lower magnitude at the site where the soil type was loamy sand.

Fig. 3 depicts the observed maxima in net radiation. Net radiation maxima were comparable for both the months at Arnej and

Table 1 : Cloud amount at the LASPEX-97 region during IOP for July and September 1997

Date	Anand	Derol	Sanand	Khandha	Arnej
JULY					
12-7-1997	No observation	No observation	No observation	Cloudy, 3/8 (Rain in passed night)	No observation
13-7-1997	Overcast.	Cloudy	Overcast	Overcast, Drizzle (Rain in passed night)	No observation
14-7-1997	Cloudy, 4/8	Cloudy	Cloudy, 4/8	Overcast, Rain	No observation
15-7-1997	Cloudy, 5/8	Cloudy	Cloudy, 4/8	Cloudy, 6/8, Rain	No observation
16-7-1997	Cloudy, 7/8	Cloudy	Cloudy, 3/8	Overcast	No observation
17-7-1997	Cloudy, 6/8, Drizzle in noon hrs. Rain in night	Cloudy, Drizzling in evening hrs	Overcast	Cloudy, 6/8	No observation
18-7-1997	Overcast, Rain in evening hrs.	Cloudy (Rain occurred in passed night)	Overcast	Overcast, Rain	No observation
SEPTEMBER					
12-9-1997	Overcast, Rain	No observation	Cloudy, 6/8, Rain in noon hrs.	Cloudy, Rain	No observation
13-9-1997	Cloudy to overcast, Rain	Cloudy, 6/8	Cloudy, 6/8, Rain in evening hrs.	Cloudy, 6/8	No observation
14-9-1997	Cloudy	Cloudy, 7/8	Cloudy, 6/8, Rain in evening hrs.	Cloudy, 6/8	No observation
15-9-1997	Cloudy to overcast	Cloudy, 7/8	Cloudy, 6/8	Cloudy, 6/8	No observation
16-9-1997	Overcast, Rain in noon hrs.	Cloudy, 7/8	Overcast, Rain in noon hrs	Cloudy, 6/8	No observation
17-9-1997	Overcast (Rain in Passed night) night)	Cloudy, 6/8	Overcast (Rain occurred passed	Cloudy, 5/8	No observation
18-9-1997	No observation	No observation	No observation	Cloudy, 4/8	No observation

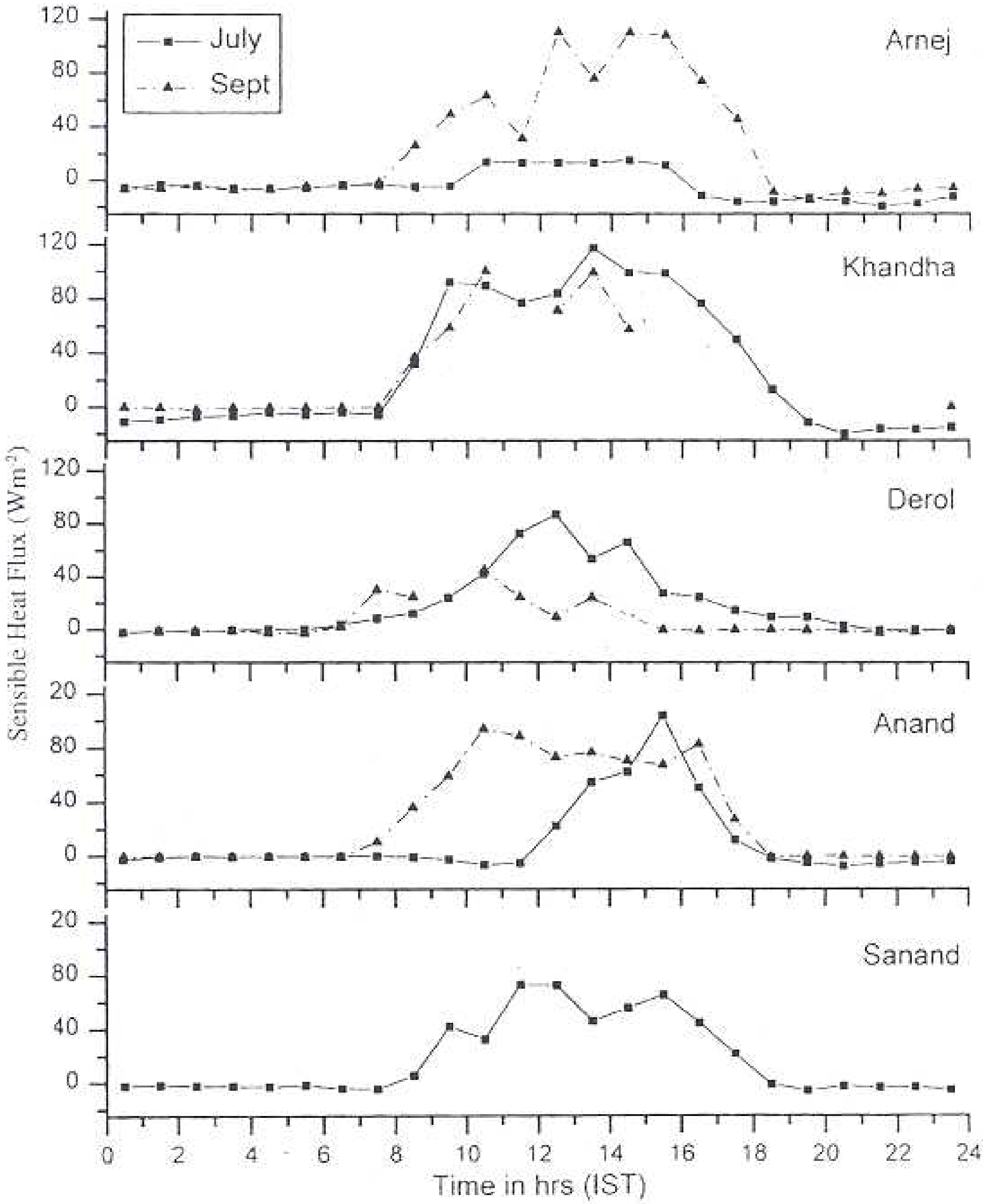

Fig. 1: Diurnal variation of sensible heat flux in July and September 1997

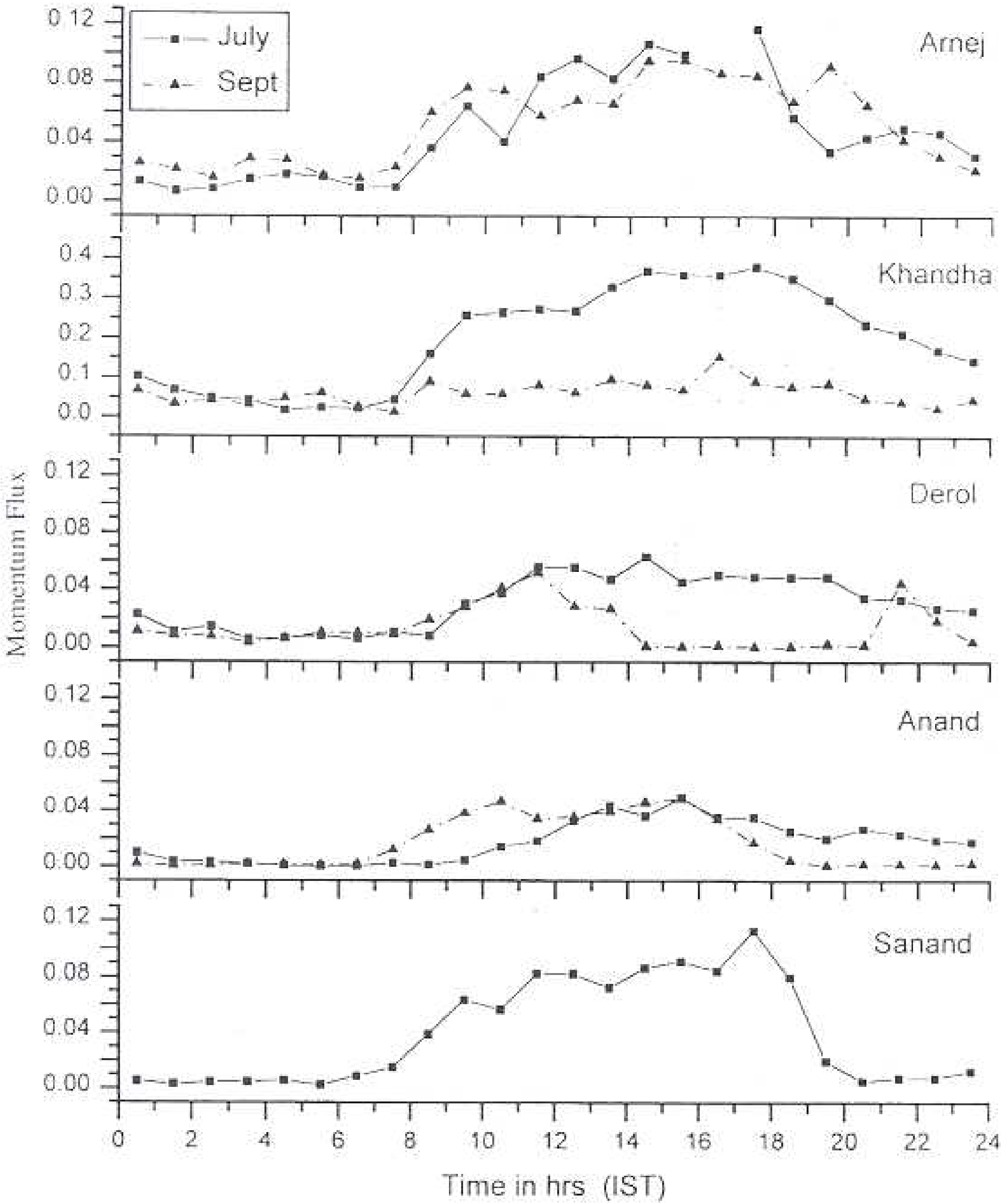

Fig. 2 : Diurnal variation of momentum flux ($m^2 s^{-2}$) in July and September 1997

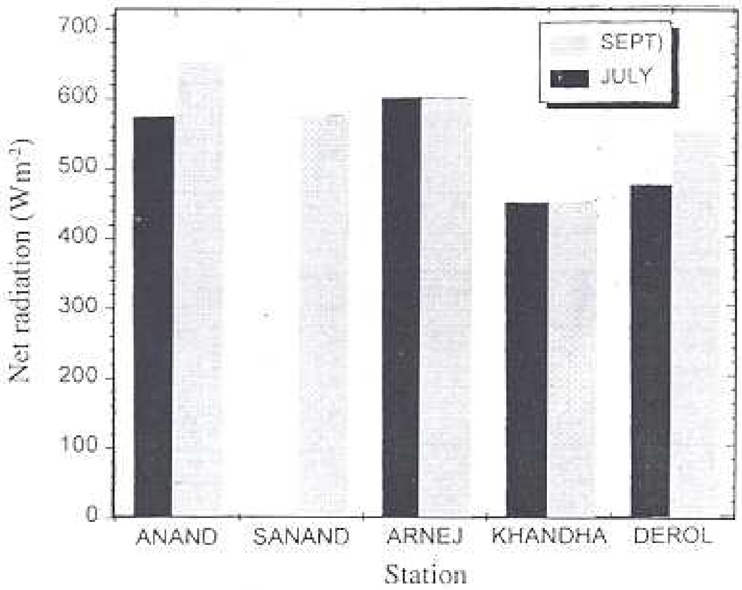

Fig. 3: Net radiation observed at peak hours in July and September 1997.

Khandha where the soil type was clay. It was higher in September than that in July at other two stations. At Sanand, radiation data are erroneous due to failure in calibration of radiation sensors for July and hence are not shown. The spatial differences in the fluxes of sensible heat, momentum and net radiation could be due to different soil and vegetation properties as well as surface pattern.

Variation of drag and heat exchange coefficient with stability

The fluxes were estimated by profile method in which stability was given by the Momin-Obukhov length (L). A nondimensional factor z/L was used as a stability parameter. Fig.4 and 5 show the variation of C_D and C_H respectively with z/L. C_H was 2-3 times larger than C_D. Both coefficients (C_D and C_H) showed decreasing trend with increasing stability in most of the cases. At Khandha, in September, they were scattered but one could see higher magnitude in unstable conditions (-ve z/L) than in stable condition.

Under neutral conditions ($z/L \simeq 0$), C_D and C_H showed higher magnitude in September than those in July. Overall, larger coefficients were observed at Arnej and Khandha. The variation of these coefficients with wind speed (Figure not shown) did not show systematic trend. Over LASPEX site, under neutral conditions, C_D varied between 0.0035 (Anand and Derol) to 0.010 (Khandha and Arnej) whereas C_H varied from 0.011 (Anand and Derol) to 0.021 (Khandha and Arnej). During MONTBLEX, over Jodhpur, which is nearer to the LASPEX site, C_D and C_H were studied by various workers (Patil and Parasnis, 2001; Kusuma, 1996; Kusuma *et.al.*, 1996; Mohanty *et.al.*,1995) using different

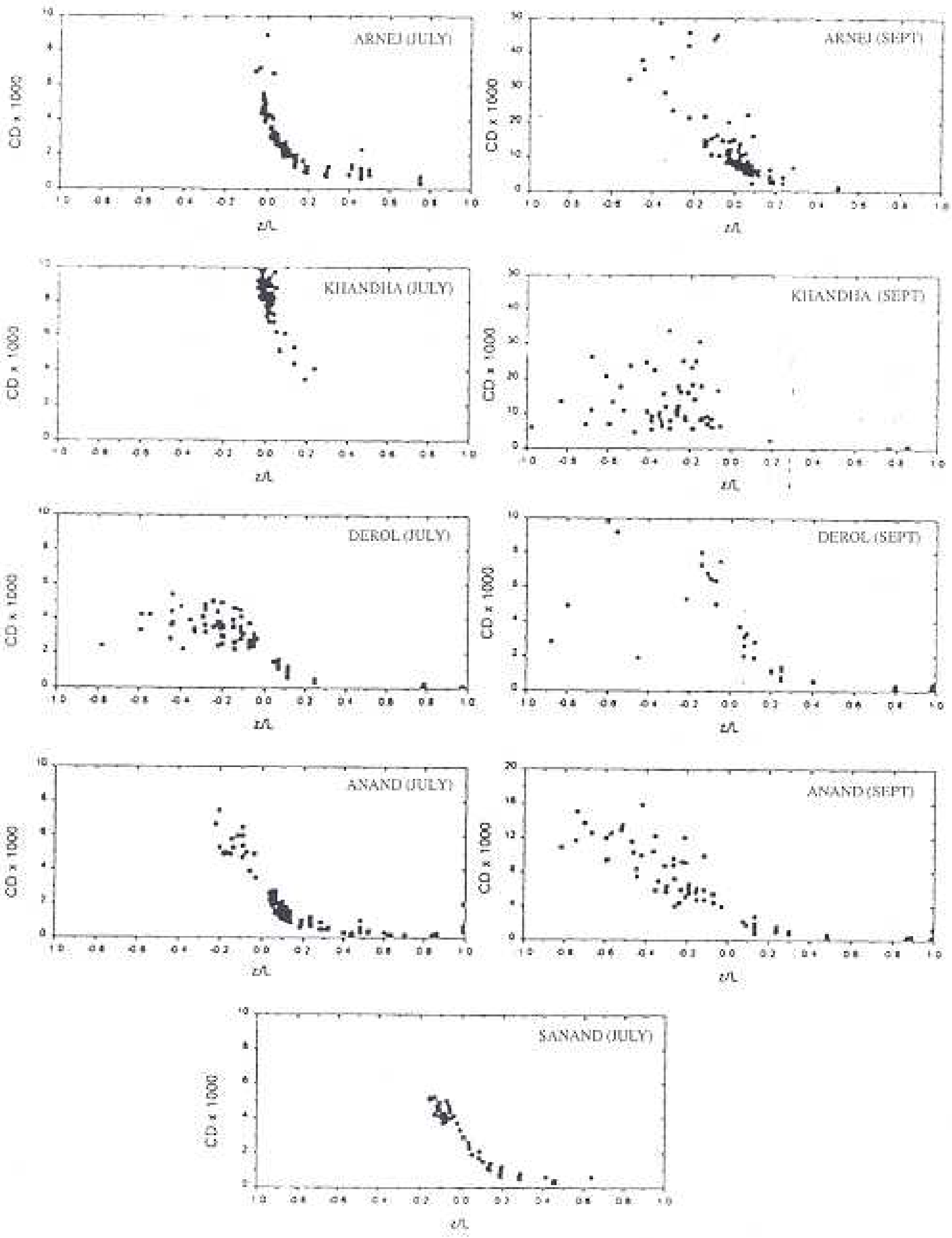

Fig. 4 : Variation of C_D with z/L over LASPEX-97 sites.

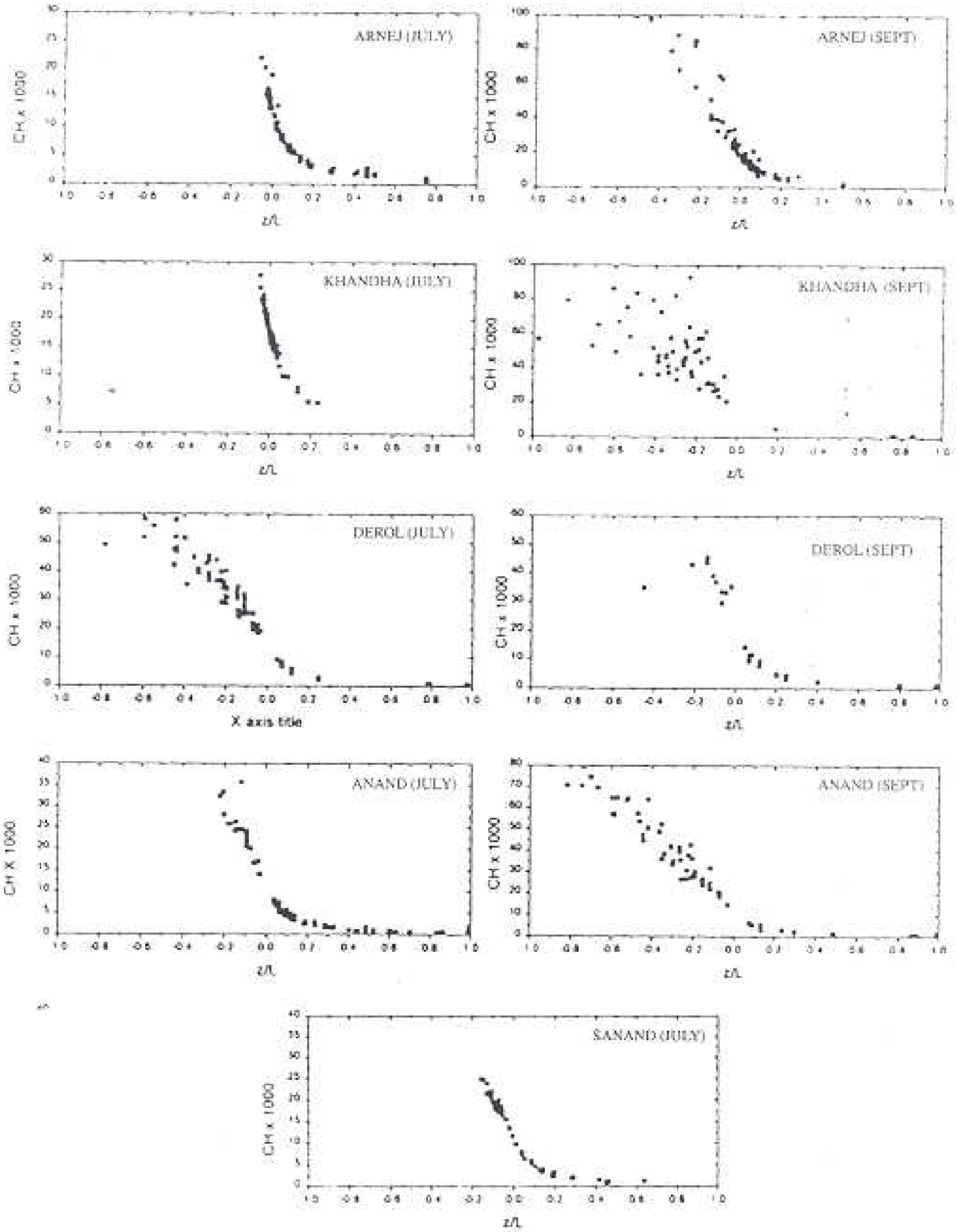

Fig. 5: Variation of C_H with z/L over LASPEX-97 sites.

techniques. The observed magnitudes of C_D and C_H are in agreement with the values reported by Patil and Parasnis (2001); Kusuma (1996) and Mohanty et.al. (1995). Observed variations in these values from station to station over LASPEX site is due to the greater variability in vegetation pattern as well as soil properties.

SUMMARY

The study of variations of fluxes and exchange coefficients using LASPEX-97 observations suggested the followings:

(i) The fluxes of sensible heat and momentum showed diurnal variations. The net radiation was higher in September as compared to that in July. In general, higher momentum flux was observed at the stations where soil type was clay; while at the stations where soil was loamy sand, the momentum flux was low.

(ii) Under neutral stability, C_D varied between $(3.5 - 8.5) \times 10^{-3}$ in July and $(5.0 - 10.0) \times 10^{-3}$ in September, while C_H varied from $(11.0 - 18.0) \times 10^{-3}$ in July and $(14.0 - 21.0) \times 10^{-3}$ in September. C_D and C_H showed decreasing trend with increase in stability. Magnitude of C_H was relatively higher (about 2-3 times) than C_D under neutral conditions. Their variation with wind speed was not systematic. These results are attributed to the soil and vegetation properties at the respective stations.

ACKNOWLEDGEMENTS

LASPEX-97 was sponsored by the Department of science and Technology, New Delhi (Govt. of India). Authors wish to thank Director, Indian Institute of Tropical Meteorology, Pune (IITM) for facilities provided for the work. Authors are thankful to Prof. A.M.Shekh, Gujarat Agricultural University and his staff for providing necessary facilities at observational site. Thanks are due to the staff members of Boundary Layer and Land Surface Processes Studies Division of IITM for their assistance in collection of observations.

REFERENCES

Beljaars, A. C. M. and Holtslag, A. A. M. 1991. Flux parameterization over land surfaces for atmospheric models. *J. Appl. Meteorol.*, 30 : 327-341.

Businger, J. A., Wyngaard, J. C. Izumi, Y.; and Bradley, E. F. 1971. The flux-profile relationship in the atmospheric surface layer. *J. Atmos. Sci.*, 28 : 181-189.

Dyer, A. J. and Hick, B. B. 1970. Flux gradient relationships in the constant flux layer. *Quart. J. Roy. Meteorol. Soc.*, 96 : 715-721.

Garratt J. R. 1977. Review of Drag Coefficients over Oceans and Continents. *Mon. Wea. Rev.*, 105 : 915-929.

Hicks, B. B. 1976. Wind profile relationships from the "Wangara" experiments. *Quart. J. Roy. Meteorol. Soc.*, 102 : 535-551.

Hogstorm, U. 1988. Nondimensional wind and temperature profiles in the atmospheric surface layer : A reevaluation. *Bound. Layer Meteorol.*, 42 : 55-78.

Holtslag, A. A. M., and DeBruin, H. A. R. 1988. Applied modelling of the nighttime surface energy balance over land. *J. Appl. Meteorol.*, 27: 689-704.

Kusuma Rao, G. 1996. Roughness length and drag coefficient at two MONTBLEX-90 tower site. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 105 (3) : 273-287.

Kusuma Rao, G., Narasimha, R. and Prabhu, A. 1996. An analysis of MONTBLEX data on heat and momentum flux at Jodhpur. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 105 (3) : 309-323.

McBean, G. A. 1979. The planetary boundary layer, Tech. Note. 165, WMO-530, pp 201

Mohanty, U. C., Parihar, P. S., Venugopal, T. and Parashuram. 1995. Estimation of drag coefficient over the western desert sector of the Indian summer monsoon trough. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 104 (2) : 273-287.

Nieuwstadt, F.T.M. 1978. The computation of the friction velocity u_* and the temperature scale T_* from temperature and wind profile by least square method, *Bound. Layer Meteorol.*, 14 : 235-246.

Patil, M.N. and Parasnis, S.S. 2001. Variations in drag, heat exchange and moisture exchange coefficient with wind speed and stability in the monsoon trough region. In Long Term Changes and Trends in the Atmosphere, Vol. II, Ed. Gufran Beig, New Age International (P) Ltd., pp. 292-302,

Paulson, C. A. 1970. The mathematical representation of wind speed and temperature profiles in the unstable atmospheric surface layer. *J. Appl. Meteorol.*, 9 : 856-861.

Shekh, A.M., Vernekar, K.G., and Keshavamurthy, R.N. 2001. The beginning of LASPEX-97. *J. Agrometeorol.*, 3 : 31 - 37.

Stull, R. B. 1988. An Introduction to Atmospheric Boundary Layer Meteorology, Kluwer Academic Publ.

Yaglom, A. M. 1977. Comments on wind and temperature flux-profile relationships. *Bound. Layer Meteorol.*, 11 : 89-102.