

Variation of boundary layer heights and eddy diffusivities over dry and moist convective regions of monsoon trough during different phases of monsoon

B. PADMANABHAMURTY and INDU JAIN

School of Environmental Sciences, Jawaharlal Nehru University, New Delhi - 110067, India

(Received 17 April 1997, Modified 3 March 1998)

सार — खड़गपुर और जोधपुर के मौसम विज्ञान टावरों के ऊपर 6 स्तरों के तापमान, पवन और आर्द्रता संबंधी आंकड़े तथा जोधपुर (4 मी. पर ध्वनिक पवनवेगमापी तथा 15 मी. पर गिल पवनवेगमापी) और खड़गपुर (8 मी. पर ध्वनिक पवनवेगमापी तथा 15 मी. पर गिल पवनवेगमापी) के स्थायी आंकड़ों का विश्लेषण किया गया है। सूक्ष्म-मौसम विज्ञान टावर आंकड़ों का उपयोग करते हुए भारतीय दक्षिणी पश्चिमी मानसून के आरम्भ, मध्य और इसकी समाप्ति की प्रावस्थाओं के दौरान मानसून द्रोणी के शुष्क संवहनी क्षेत्र जोधपुर (26.3° उ., 73° पू.) तथा आर्द्र संवाहनी क्षेत्र खड़गपुर (22.3° उ., 87.2° पूर्व) को परिसीमा स्तर ऊँचाई के दैनिक परिवर्तन और गति, ऊष्मा व नमी के भंवर विसरणशीलता गुणांक का अध्ययन किया गया है। परिसीमा स्तर ऊँचाई का आकलन भंवर सहसंबद्ध (प्रत्यक्ष विधि) तथा प्रोफाइल विधि (अप्रत्यक्ष विधि) द्वारा किया जाता है। अप्रत्यक्ष विधि में परिसीमा स्तर ऊँचाई को कम महत्व दिया जाता है।

ABSTRACT. Temperature, wind, and humidity data at 6 levels over meteorological towers at Kharagpur and Jodhpur and fast data at Jodhpur (Sonic anemometer at 4m and Gill anemometer at 15m) and Kharagpur (Sonic anemometer at 8m and Gill anemometer at 15m) were analysed. Diurnal variation of boundary layer heights and eddy diffusivity coefficient of momentum, heat and moisture at dry convective region Jodhpur (26.3°N, 73°E) and moist convective region Kharagpur (22.3°N, 87.2°E) of monsoon trough during onset of monsoon, mid-monsoon and end-monsoon phases of the Indian southwest monsoon are studied using micro-meteorological tower data. Boundary layer height is computed by eddy correlation (direct method) and profile method (indirect method). Indirect method underestimates the boundary layer height.

Key words— Atmospheric boundary layer height, Eddy diffusivity, Eddy correlation method, Profile method.

1. Introduction

Atmospheric Boundary Layer (ABL) is that part of the atmosphere which is directly affected by the surface of the earth. This is of importance due to its ability to diffuse mass, momentum and heat across it. Almost all the heat and moisture present in the atmosphere comes from the surface and transported through this layer. Turbulence is primarily responsible for this transport. Study of this boundary layer is important for much of human activity exists within it and its dynamics plays a key role in the dynamics of the entire atmosphere.

ABL is equally important in air pollution studies, because the dispersal and dilution of pollutants is mainly guided by the meteorological regime of the ABL besides the source strength.

Despite its importance, surprisingly systematic scientific investigations of the ABL are confined to the last few decades only. In view of this, in the present paper the study of diurnal variation of boundary layer heights and coefficients of eddy diffusivity of momentum, heat and moisture for the onset, mid-monsoon and end-monsoon, using micro-meteorological tower data during the Pilot experiment phase of Monsoon Trough Boundary Layer Experiment (MONTBLEX) in 1990 was made.

Though less attention has been paid to the diurnal variation of boundary layer heights and eddy diffusivity coefficients of momentum, heat and moisture under tropical conditions, some studies are reported on the turbulence characteristics of the Surface Boundary Layer (SBL) in the tropics. (Padmanabhamurty 1981, Mohanty *et al.* 1992,

Singhal *et al.* 1993, Chakrabarty and Padmanabhamurty 1995, P. Agarwal *et al.* 1995, Kusuma *et al.* 1995 & 1996).

2. Description of data set

In the present study, slow as well as fast response data from the towers collected at Kharagpur (KGP) and Jodhpur (JDP) for three representative days in different phases of monsoon (Onset, Mid and End-monsoon) during MONTBLEX, 1990 were utilized. The entire MONTBLEX raw data set for four months was processed for further analysis (Rudrakumar and Prabhu 1991, Rudrakumar *et al.* 1991b).

At JDP, the representative days chosen for analysis are 19 July, 10 August and 8 September for the onset, mid-monsoon and end-monsoon phases. Corresponding to the same phases of monsoon the days selected for analysis at KGP are 12 June, 18 August and 15 September. For details about the synoptic conditions prevailing during these periods, readers may refer to the Weather Summary given by Rudrakumar *et al.* (1991a), Srivastav (1995) and Kusuma *et al.* (1995).

3. Analysis of Data

3.1. Computation of mean gradients

The mean gradients of wind and temperature were determined using the observations from the slow response sensors. In the present study, gradients are determined using finite difference approximations. The wind shear at 4m and 8m were found from measurements at 1m and 8m levels, and at 1m and 15m levels respectively. For wind shear at 15m, 1m and 30 m levels were used.

3.2. Determination of boundary layer height and coefficient of eddy diffusivity

Boundary-layer height, is an important scaling factor for the height above the surface and for the mean and turbulent structure of this layer where the bulk of heat and moisture exchanges take place, is determined by the eddy correlation method and profile method. Eddy correlation method involves the direct determination of covariances using data from fast response sensors, avoiding assumptions about relationships between vertical fluxes and gradients. Observations from the Sonic anemometer for both the stations have been used for the determination of K_m , K_h , K_w and h . In order to obtain all significant high frequency contributions, the ratio of the path length of the instrument to the height above the ground should be less than 0.08, which is satisfied in the case of Gill as well as Sonic anemometer (Brook 1974). Time series were generated for all the variables in each run and the fluctuations were computed by subtracting the mean from the instantaneous values. The

covariances of the fluctuations have been determined by averaging the products of the appropriate fluctuations.

4. Methodology

4.1. Eddy diffusivity of momentum (K_m)

Eddy viscosity relationships

$$\overline{u'w'} = -K_m \left(\frac{\partial U}{\partial z} \right) \quad (1)$$

where, K_m is eddy diffusivity of momentum, $\overline{u'w'}$ is the turbulent flux of momentum in vertical direction and U is the mean wind.

4.2. Eddy diffusivity of heat (K_h)

Eddy diffusivity of heat, K_h , has been evaluated using the following expression

$$\overline{\theta'w'} = -K_h \left(\frac{\partial \theta}{\partial z} \right) \quad (2)$$

where $\overline{\theta'w'}$ is the turbulent flux of heat in the vertical direction and θ is the mean potential temperature.

4.3. Eddy diffusivity of moisture (K_w)

Eddy diffusivity of moisture, K_w , has been determined through the following relation

$$\overline{q'w'} = -K_w \left(\frac{\partial Q}{\partial z} \right) \quad (3)$$

where, $\overline{q'w'}$ is the turbulent flux of moisture in the vertical direction and Q is the mean humidity.

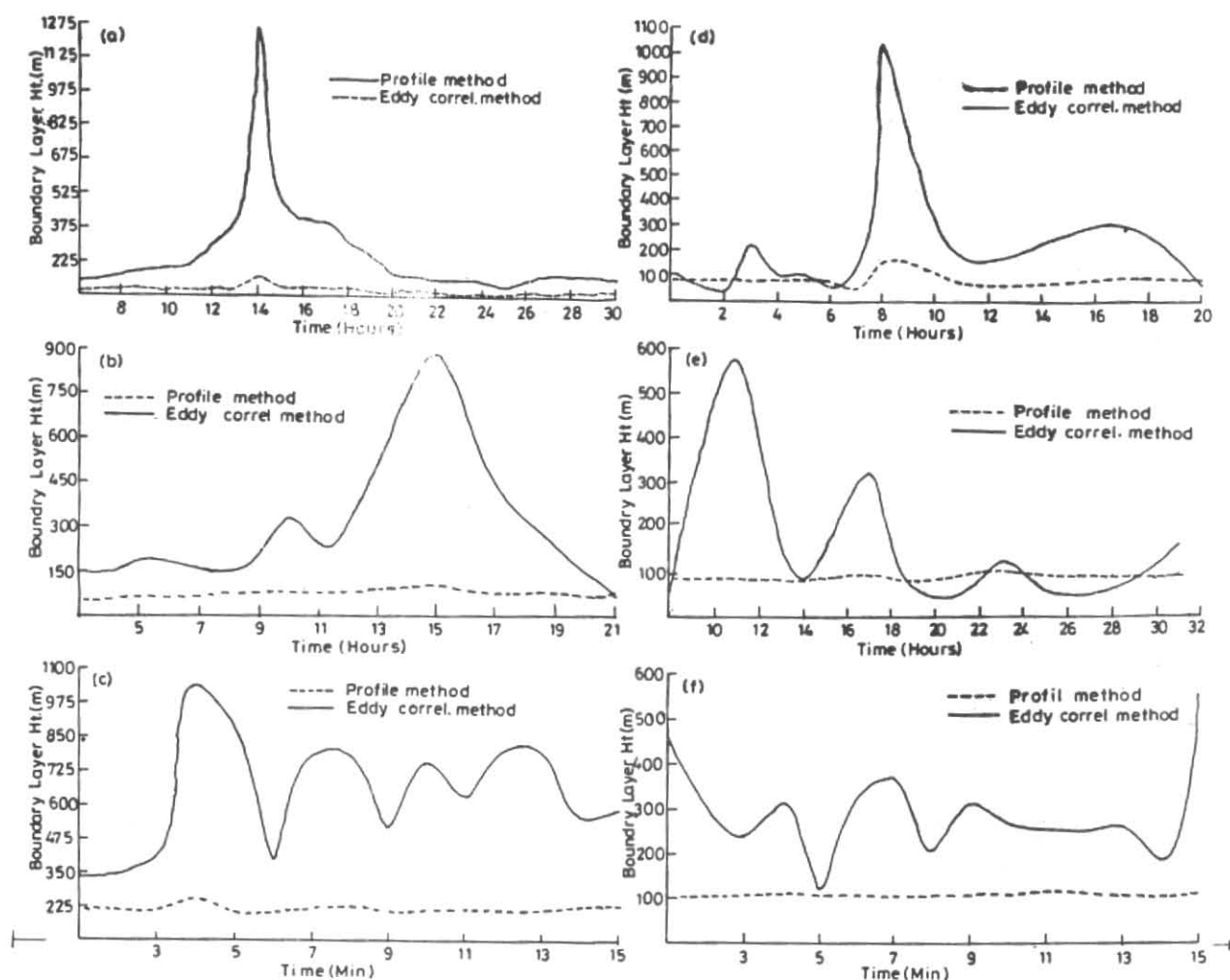
4.4. Planetary boundary layer height (h)

Planetary Boundary Layer Height, h , has been determined through the following relation (Zilitinkevich, 1972)

$$h = (\sqrt{3} k R_{if})^{1/2} \left(\frac{u_* L}{f} \right)^{1/2} \quad (4)$$

where, k is the von Karman constant, f is coriolis parameter, u_* is frictional velocity, L is Monin-Obukhov length and R , is flux Richardson number.

$$R_{if} = \frac{g}{T} \overline{w'\theta'} \\ = \frac{g}{\theta} \frac{\overline{w'\theta'}}{\overline{u'w'} \frac{\partial \bar{u}}{\partial z} + \overline{v'w'} \frac{\partial \bar{v}}{\partial z}} \quad (5)$$



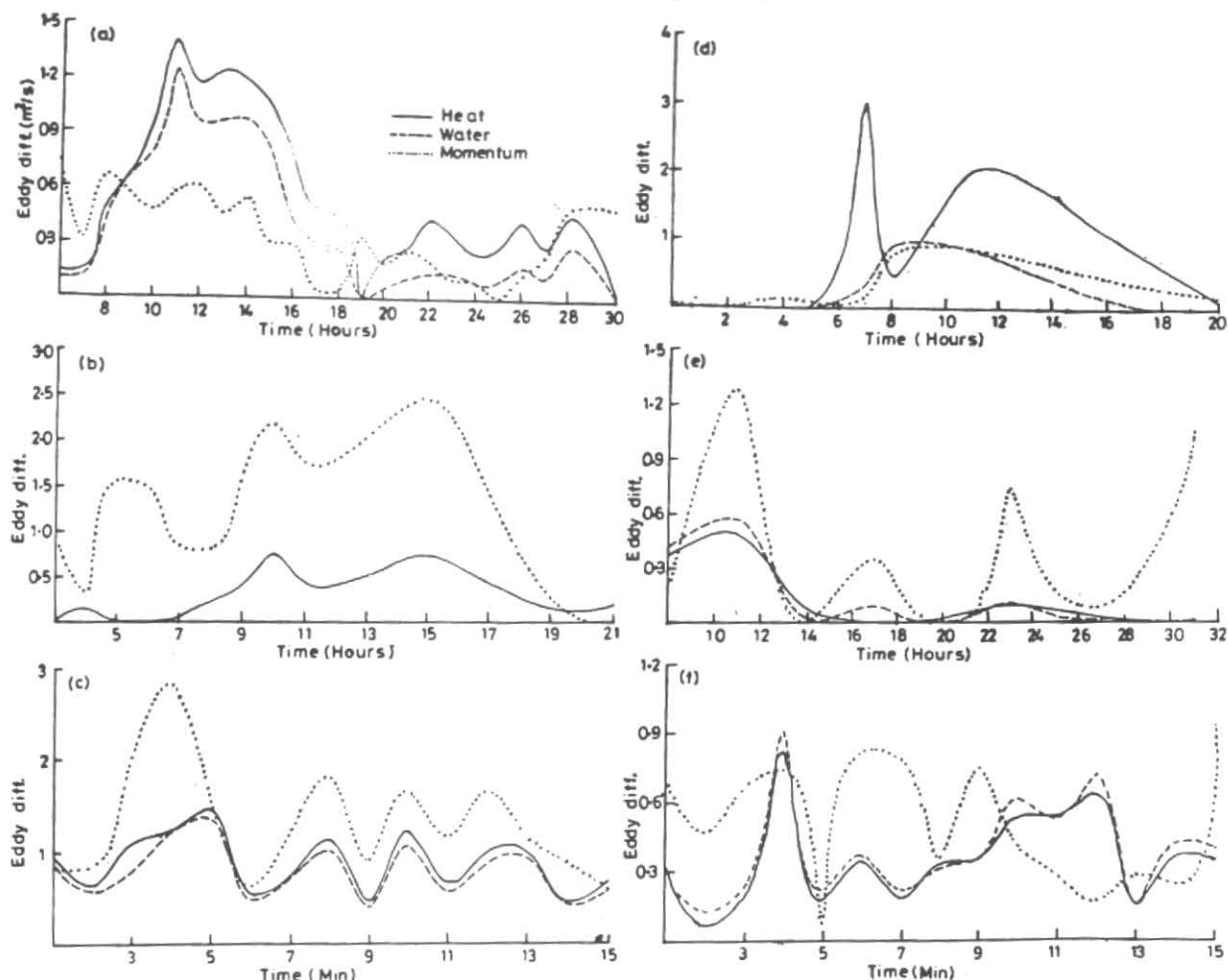
Figs. 1 (a-f). Diurnal variation of K_m , K_h and K_w at (a-c) Jodhpur and (d-f) Kharagpur during onset of monsoon, mid-monsoon and end-monsoon

5. Results and discussion

The diurnal variation of exchange coefficients K_m , K_h and K_w during onset, mid-monsoon and end-monsoon phases are shown in Figs. 1 (a-c) for JDP at 4m and Figs. 1(d-f) for KGP at 8m. During the onset phase it can be seen from Sonic (4m) anemometer data that the diurnal variation of K_h and K_w computed by first-order closure approximation for fluxes $\overline{w'\theta'}$ and $\overline{w'q'}$ at JDP, shows similar trend and most of the time K_h is higher than K_w and K_m , which could be from increasing buoyancy effects due to turbulence and thermals of warm air rising from the ground. Daytime strong winds with maximum speed of 4 to 6 ms^{-1} found during this period, presumably caused vigorous mixing in SBL. In the early morning hours, K_m is higher than K_h and K_w , suggesting the utility and validity of gradient-transport relations. K_m and K_w are in close agreement till noon compared to after-

noon, indicating the dominance of buoyancy generated turbulence at 4m height.

During the monsoon period, at JDP, it can be seen that K_h values are lower under the unstable conditions as compared to onset period. During the monsoon phase K_m is higher than K_h values, indicating dominance of mechanically generated turbulence in the surface layer. Due to nonavailability of humidity data at JDP, during mid-monsoon phase, humidity related parameter, K_w could not be studied. As sufficient data for the end-monsoon period for both the stations were not available to study the diurnal variation, only one data set has been taken for the computation at 1430 (IST) on September 1990. The behavior of K_m , K_h and K_w by eddy correlation method during the end-monsoon phase for JDP and KGP from 1430 to 1445 hr (IST) is shown in Figs. 1 (c & f).



Figs. 2(a-f). Diurnal variation of boundary layer height (m) at (a-c) Jodhpur and (d-f) Kharagpur during onset of monsoon, mid- monsoon and end-monsoon

During end-monsoon phase for both the stations, again K_m and K_w show similar trend and K_m is much higher than the other two coefficients of heat and moisture, indicating the dominance of mechanical turbulence in the surface layer. However, fluctuations are more at KGP compared to JDP. During the onset phase, at KGP, it can be seen from Sonic (8m) anemometer data that the diurnal variation of K_m and K_w shows similar trend and for most of the time K_h is much higher than K_m and K_w , which could be from increasing buoyancy effects due to turbulence from the ground during the day time. But during monsoon period, K_h and K_w , are in close agreement and K_m is much higher with large variability compared to coefficients of heat and moisture, indicating that the turbulent flux of momentum being independent of local gradient and turbulent parameters are not reflecting the effect of heat capacity of the surface.

During all the three periods investigated, at JDP 4m level and KGP at 8m level, K_m has much higher values than those reported in extra-tropical countries (Haltiner and Mar-

tin 1957). The values are in accordance with those reported by Padmanabhamurty (1981) at Visakhapatnam, India.

Boundary layer heights are related to the dynamics of the monsoon trough during the monsoon. The diurnal variation of boundary-layer heights during the onset, mid-monsoon and end-monsoon periods are shown for JDP Figs. 2(a-c) and KGP Figs. 2(d-f). These stations are representative of the two different regimes of the monsoon trough of different activities. JDP is an area of dry convective activity and KGP represents the deep moist convection of the monsoon trough. Temporal variation of height of the boundary layer for both the stations for all the three period is quite pronounced. Boundary layer heights varied from 50m to 1275m over these two stations; however the variability is different between the stations. One common feature is the occurrence of shallow boundary layer about 100m or less during early morning hours and night, indicating that the PBL formation and increase in height is a day time phenomenon only.

At JDP, another interesting feature one can infer from Figs. 2(a-c) is the growth of boundary layer height which slowly increases during morning hours and attains maximum 1275m in the afternoon (1400-1500 hr IST). This indicates that at JDP, being a region of dry convective activity, the radiant inputs and outputs are large and the atmosphere is usually very dry and clear because water vapour content is low, and cloud is generally absent. As a result very strong solar radiation reaches the surface. The impact of strong solar input will have relatively high albedo. Mainly as a result of 'Soil' factor, the surface does become very hot, and hence the outgoing long wave radiation is also great. As a result of large reflection and emission, the net radiation is absorbed by a surface and lack of moisture and more concentration of heat in the upper most layer produces vigorous mixing in the atmosphere, so PBL height is found to be higher, indicating the growth of the convective boundary layer reaching large heights during the day time. And again boundary layer height gradually decreases during transition period, and remains more or less steady under stable/night time condition. Computed results show boundary layer heights reach maximum values during daytime, induced by strong surface heating and convection.

During monsoon period boundary layer height is maximum about 900m which is less than the height observed during onset period. This may be due to cooler air brought by precipitation by clouds on the warmer ground during monsoon. PBL height again increases and attains a maximum of 1050m during end-monsoon phase, indicating the withdrawal of the monsoon.

At KGP, during onset period, maximum boundary layer height of 1050m is observed before noon which gradually decreases to about 75m during night. This is due to the absence of solar input at the ground after sunset. But during the monsoon, PBL height attains a maximum 550m and decreases to about 50m during night. No significant difference is found in the height of boundary layer between monsoon and end-monsoon phases. This could be due to persistent monsoonal air over KGP till the end of the monsoon period which is reflected in the soil moisture depletion occurring slowly during end-monsoon period. The boundary layer height during onset period is high compared to other two seasons, indicating the growth of the convective boundary layer height is large during this period, especially at unstable/daytime conditions. Hence, at JDP, maximum heights are observed for the three phases of monsoon investigated compared to KGP, PBL height however, depends on the position of the monsoon trough and difference of the air masses over the dry and moist regions.

6. Conclusions

Salient features of the study are given below :

- (i) Eddy diffusivity coefficients K_m , K_h , K_w and planetary boundary layer height are computed by eddy correlation method, at JDP and KGP for onset, mid-monsoon and end-monsoon phases by using fast as well as slow response data collected over micro-meteorological tower during the pilot experiment phase of Monsoon Trough Boundary Layer Experiment (MONTBLEX) in 1990.
- (ii) PBL heights during the onset attain maximum values at JDP and KGP during unstable/daytime conditions, because of strong surface heating and convection. But lower values are attained during mid-monsoon period due to the monsoonal air and cloudy conditions prevalent over the two stations. During end-monsoon period, again PBL heights increased at JDP due to induced free convection.
- (iii) At KGP, no significant difference is found in PBL height : maximum. PBL height remained same in monsoon and end-monsoon periods. This indicates that the monsoonal air mass prevails till the end of monsoon over the region. And PBL height is not constant with time but it depends upon the strength of the surface generated mixing.
- (iv) By day, when earth's surface is heated by the sun, there is an upward transfer of heat into the cooler atmosphere. This vigorous thermal mixing (convection) enables the PBL height to extend higher during onset period compared to other two seasons.
- (v) The diurnal variation of the eddy diffusivity coefficients indicates that during onset period at JDP and KGP K_h is higher than K_w and K_m . But K_m is higher than other two during monsoon as well as end-monsoon period at both stations. This indicates that free convection is occurring during onset period whereas forced convection is dominant during monsoon as well as for end-monsoon periods.
- (vi) It is observed that PBL height is not affected either by eddy diffusivities of heat and water vapour individually or relatively.

Acknowledgement

The authors acknowledge with thanks the Ministry of Science and Technology, Govt. of India, New Delhi for providing financial assistance as well as MONTBLEX data.

References

- Agarwal, P., Yadav, A.K., Gulati, A., Raman, S., Rao, S., Singh, M.P., Nigam, S. and Reddy, N., 1995, "Surface layer turbulence processes in low wind speeds over land", *J. Atmos. Environ.*, **29**, 2089-2098.

- Brook, R.R., 1974. "A study of wind structure in an urban environment". Met. Study No. 27, Australian Government Publishing Service, Canberra.
- Chakrabarty, P. and Padmanabhamurty, B., 1995. "Some Surface Layer Parameters during Onset and Mid monsoon phases of MONTBLEX-90 at Jodhpur", *Vayu Mandal*, **25**, 1-2, 33-40.
- Haltiner, G.J. and Martin, F.L., 1957. "Dynamical and Physical Meteorology", McGraw Hill, New York, 253.
- Kusuma Rao, G., Raman, S., Prabhu, A. and Narasimha, R., 1995. "Turbulent heat flux variation over the monsoon-trough region during MONTBLEX-90", *Atmos. Environ.*, **29**, 16, 2113-2129.
- 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.
- Mohanty, U.C., Venugopal, T., Parashuram, and Parihar, P., 1992. "Study of structure of surface layer at Kharagpur using MONTBLEX data", Workshop on preliminary scientific results on MONTBLEX, Jan 16-17, IIS, Bangalore. 23-33.
- Padmanabhamurty, B., 1981 "A preliminary analysis of tower meteorological data during December 1978 at Visakhapatnam", *Mausam*, **32**, 2, 165-174.
- Rudrakumar, S. and Prabhu, A., 1991. "Quality assessment of the tower data from MONTBLEX-90", Report 91, MD 3; Centre for atmospheric Sciences, IISc, Bangalore, India.
- Rudrakumar, S., Srinivasan, H.P., Srikrishna, R., Ameenullah, S. and Prabhu, A., 1991a. "Available tower data from MONTBLEX-90", Report 91, MD 1, Centre for Atmospheric Sciences, IISc, Bangalore, India.
- Rudrakumar, S., Srinivasan, H.P., Satyadev, H.N., Ameenullah, S. and Prabhu, A., 1991b. "Surface layer data from MONTBLEX-90", Report 91, MD 2; Centre for Atmospheric Sciences, IISc, Bangalore, India.
- Singhal, S. P., Gera, B.S. and Ojha, V.K., 1993. "Sodar studies of the monsoon trough boundary layer at Jodhpur (India)", *Mausam*, **44**, 1, 9-14.
- Srivastav, S.K., 1995. "Synoptic meteorological observations and weather conditions during MONTBLEX-90", *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **104**, 189-220.
- Zilitinkevich, S.S., 1972. "On the determination of the Ekman Boundary Layer", *Boundary Lay., Meteorol.*, **3**, 141-145.
-