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Fluxes over Varanasi during intensive observational period of MONTBLEX-90

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सार — वाराणसी में, 27 जुलाई 1990 को, झंझावात और सतही तल पर इसके प्रभाव का अन्वेषण करने के लिए, एक गहन-प्रेक्षण अवधि (आई० ओ० पी०) हेतु मांटब्लेक्स-90 के आंकड़ों का प्रयोग किया गया है। प्रोफाइल, एरोडाइनेमिक और एडी सहसंबंध विधियों द्वारा संवेद्य ऊष्मा फलक्स का परिकलन किया गया है। इसके साथ-साथ झंझावात से पूर्व, झंझावात के समय तथा उसके पश्चात् पाई जाने वाली दशाओं के तुलनात्मक निदान हेतु संवेग और आर्द्रता फलक्स का परिकलन भी किया गया है। फलक्स के मात्रात्मक परिकलन के लिए मोनिन-ओबुखोव समानता सिद्धांत का प्रयोग किया गया है। परिणामों से ज्ञात हुआ है कि झंझावात के समय सतह अधिक उत्प्लावक होती है। इस प्रभाव के अधीन आर्द्रता एवं संवेग फलक्स के अधिकतम मान झंझावात के समय ही प्राप्त होते हैं। जबकि ऊष्मा फलक्स झंझावात से पहले अधिकतम पाया गया है। इस अध्ययन के परिणामों से, स्थायी एवं अस्थायी दशाओं के दौरान, सतही तल में प्रक्षुब्ध स्थानांतरण को ठीक प्रकार से समझा जा सकता है।

ABSTRACT. MONTBLEX-90 data for an Intensive Observational Period (IOP) was extracted to investigate the thunderstorm and its impacts on surface layer at Varanasi on 27 July 1990. Sensible heat flux has been computed by profile, aerodynamic and eddy correlation methods. In addition to that, momentum and moisture fluxes have been computed for comparative diagnosis of situations before, at the time and after thunderstorm. Monin-Obukhov similarity theory has been used for quantification of the fluxes. Findings indicate that surface is more buoyant at the time of thunderstorm. Under this influence, maxima of moisture and momentum fluxes occur at the time of thunderstorm. However, heat flux was found to be maximum before the thunderstorm. The results provide an understanding of surface layer turbulent transfer during stable and unstable conditions.

Key words — Flux, Momentum, Thunderstorm, Richardson number, Sensible heat, Moisture flux.

1. Introduction

Monsoon trough is one of the prominent components of southwest monsoon in India. It is regarded as the convergent zone, with substantial moisture incursion in lower level. Lot of convective activity also occurs over this area during southwest monsoon causing thunderstorm. Monsoon Trough Boundary Layer Experiment (MONTBLEX)-90 was conducted to collect data over the monsoon trough region to understand land surface processes during monsoon (Goel and Srivastava 1990). Many research studies in the surface layer near monsoon trough region have been undertaken by several scientists during the last 2-3 years. Moisture is generally present in a shallow layer near the surface and is vertically transferred upward under unstable condition. Instability is controlled by surface layer wind and thermal structure and when atmosphere is unstable, sensible heat, momentum and moisture are transferred upwards. These vertical fluxes are modified under different weather conditions and prevailing meteorological situations in space and time. Thunderstorm activity is the manifestation of the instability in the Planetary Boundary Layer (PBL).

Growth of thunder-cloud is maintained by supply of moisture from sub-cloud layer which has been removed from surface layer by upward transport mechanism. Lower layer of atmosphere is capable of releasing a considerable amount of moisture flux to develop a convective cloud or activate it (Ray Choudhary 1951). The surface layer contains bulk of moisture and has greatest potential buoyancy for moist adiabatic ascent in an unstable tropical atmosphere. Buoyant production term is responsible to increase vertical momentum transport so that it can compensate the larger frictional losses of momentum which are experienced over land (Bergstrom and Johanssan 1988). The purpose of this study is to visualize the role of sensible heat, moisture and momentum fluxes and stability parameter with the development of thunder-cloud and to analyze the impact of thunderstorm in modulating fluxes over Varanasi. Occurrence of thunderstorm has been identified according to operational practice existing in India Meteorological Department

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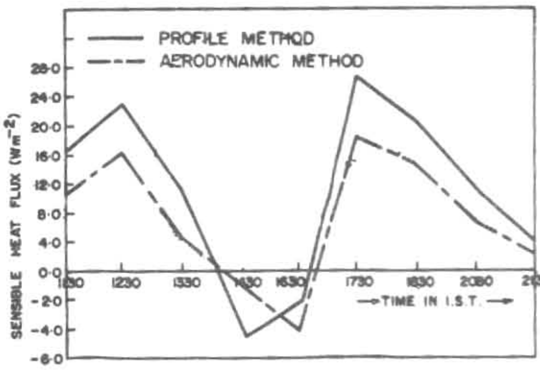


Fig. 1. Sensible heat flux at Varanasi on 27 July 1990 (I.O.P.)

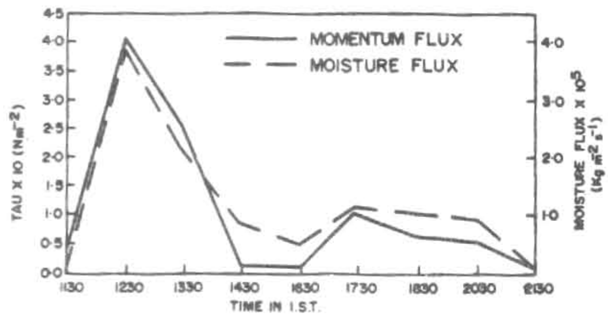


Fig. 2. Momentum and moisture flux during Intensive Observational Period (I.O.P.)

(IMD) at the observing station. It may be mentioned that no study has been undertaken to calculate the fluxes in the surface layer over India during thunderstorm. Three methods, namely, profile, aerodynamic and eddy correlation have been used for the study.

2. Data

MONTBLEX-90 fast response data for Varanasi as well as surface observations for the station were used in this computation. Micro-meteorological tower data comprising meteorological elements, *viz.*, temperature, wind speed and relative humidity at 1, 2, 4, 8, 15 and 30 m (*i.e.*, 6 levels) have been taken and Sonic and Gill anemometer data for u, v and w components of wind at levels 2 (2 m) and 5 (15 m) have been used to compute surface layer fluxes, *i.e.*, sensible heat, momentum, moisture fluxes and Richardson number. In addition to these, weather situations were studied to select the dates.

There were thunderstorms on 27 July 1990 at Varanasi during active monsoon condition in the plains of Uttar Pradesh. During an active monsoon phase, we have continuous set of hourly observations from 1130 to 2130 hrs IST during Intensive Observational Period (IOP). There was continuous drizzle and rain. But there was thunderstorm at a particular time, period ranging from 1215 to 1410 hrs IST and 1940 to 2045 hrs IST. There was continuous rain from 1410 to 1540 hrs IST and from 1540 to 1940 hrs IST there was neither rain nor thunderstorm. On 3 July 1990 there was thunderstorm at 1730 hrs IST and rain at 1430 hrs IST. This date was selected to study the influence of thunderstorm on surface layer.

3. Methodology

There are three standard methods to compute fluxes in the surface layer. These methods are based on definite hypothesis for estimation of fluxes. Sensible heat, momentum and moisture fluxes have been parameterized in such a manner that it required different derived variables for different methods. These derived parameters were obtained by using tower data by following methods.

3.1. *Profile method*

The Monin-Obukhov similarity theory has been utilised to study stable and unstable surface layer. Wind and temperature profile relationship are given below :

$$\frac{\partial u}{\partial z} = \frac{u_*}{kz} \phi_m (z/L) \quad (1)$$

$$\frac{\partial \theta}{\partial z} = \frac{\theta_*}{kz} \phi_h (z/L) \quad (2)$$

$$C_D = u_*^2 / u(z)^2 \quad (3)$$

$$L = u_*^2 \theta / k g \theta_* \quad (4)$$

where, u_* — frictional velocity; θ — potential temperature; θ_* — scaling potential temperature; k — Von-Karman constant; $\phi_m (z/L)$ — dimensionless wind gradient; $\phi_h (z/L)$ — dimensionless temperature gradient; z/L — stability parameter; L — Monin-Obukhov length; C_D — drag coefficient and $u(z)$ — mean wind speed at height z where, z = 1, 2, 4, 8, 15 and 30 m.

The Eqns. (1) & (2) have been integrated and stability function has been calculated at each level following Paulson (1970) and Businger *et al.* (1971). Initially u_* and θ_* are computed from Eqns. (1) & (2) under neutral condition. Then, L is computed using Eqn. (4). u_* and θ_* are recomputed following Mohanty *et al.* (1992) and these iterations continue till frictional velocity and scaling potential temperature remained unchanged. for two successive

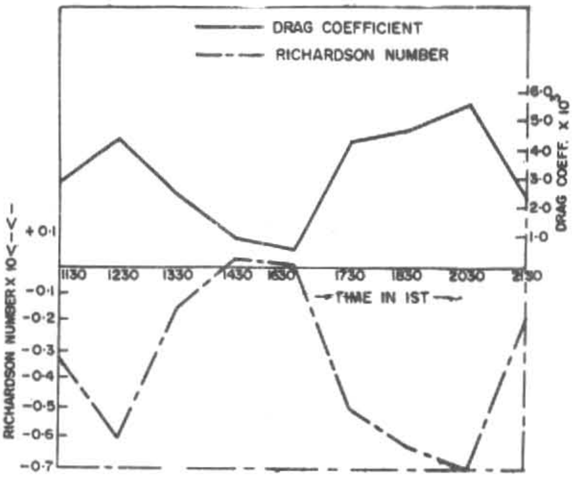


Fig. 3. Drag coefficient and Richarson number for Varanasi on 27 July 1990

interations. The computation was carried out for each level.

Finally, sensible heat momentum fluxes, Monin-Obukhov length and Richardson number have been computed by the following relations as :

$$\mathrm{SH} = -\rho C_p u_* \theta_*,\ \tau = \rho u_*^2, \text{ and } R_i = \frac{g(\partial\theta/\partial z)}{\theta(\partial u/\partial z)^2}$$

where, SH — sensible heat flux; τ — momentum flux; R_i — Richardson number and C_p — specific heat at constant pressure and rest terms signify usual meaning.

3.2. *Bulk aerodynamic method*

Average values of temperature, wind speed and relative humidity have been estimated at all six levels. Specific humidity at these levels has been computed by using Clausius-Clapeyron equation and fluxes were derived by using following relations,

$$\tau = \rho C_D u(z)^2,$$

$$\mathrm{SH} = \rho C_p C_D (T_z - \tau_{z+1}) u(z),$$

$$E = \rho C_E (q_z - q_{z+1}) u(z)$$

where, q — specific humidity; E — moisture flux and C_D & C_E are empirical constants. Numerical values of these transfer coefficients are in the same range of that of Pond *et al.* (1974).

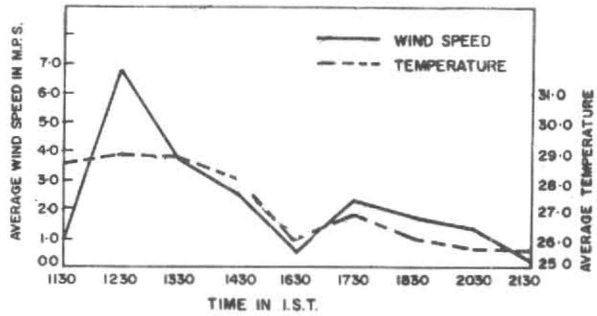


Fig. 4. Average wind speed and temperature for 30 m thickness of surface layer

3.3. *Eddy correlation method*

Sensible heat flux was calculated by the formula,

$$\mathrm{SH} = \rho C_p w'T'$$

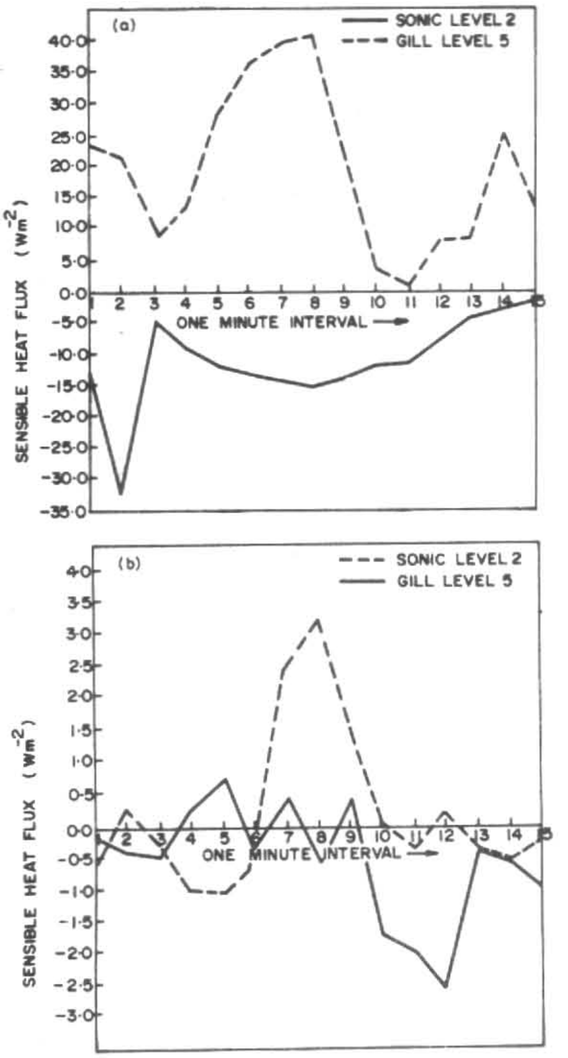
where w' and T' are fluctuating vertical components of velocity and temperature respectively.

Sonic and Gill anemometers were installed at 2 and 15 m height. Turbulent terms u', v', w' and T' have been taken at every cycle of observation. Then, one minute mean of $w'T'$ has been computed.

In view of comparing temporal trend of sensible heat flux at 2 and 15 m height by profile and aerodynamic methods with eddy correlation technique, gradient of wind speed and temperature between 2-15 m and 15-30 m have been considered, and average values for 15 minutes have been compared.

4. Results and discussion

Net vertical transfer of sensible heat, momentum and moisture fluxes has been computed from 8 Hz data. Algebraic sum of fluxes at all six levels has been taken, which is shown in Figs. 1 & 2. Similarly, mean values of drag coefficient and algebraic sum of Richardson number were com puted for 30 m thickness of surface layer using the computed values at all six levels respectively. The mean values are shown in Fig. 3. Similarly, average wind speed and temperature for 30 m layer are shown in Fig. 4. Fast Sonic and Gill data are used to calculate fluxes for one minute interval at 2 and 15 m levels respectively by eddy correlation method. Two data sets have been taken for computation at 1330 and 1430 IST on 27 July 1990 during IOP, to study the fluxes at the time and after thunderstorm. Figs. 5 (a & b) show behaviour of sensible heat flux by eddy



Figs. 5 (a & b). Sensible heat flux by eddy correlation method on 27 July 1990 during 1430-1445 hrs (IST) at (a) 2 m and (b) 15 m height

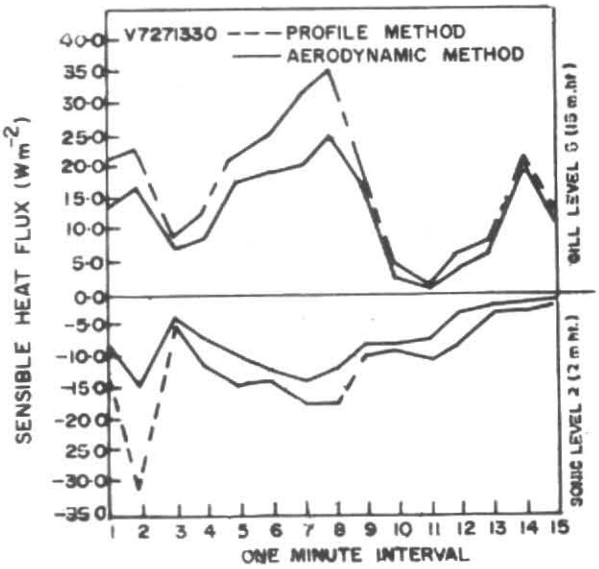


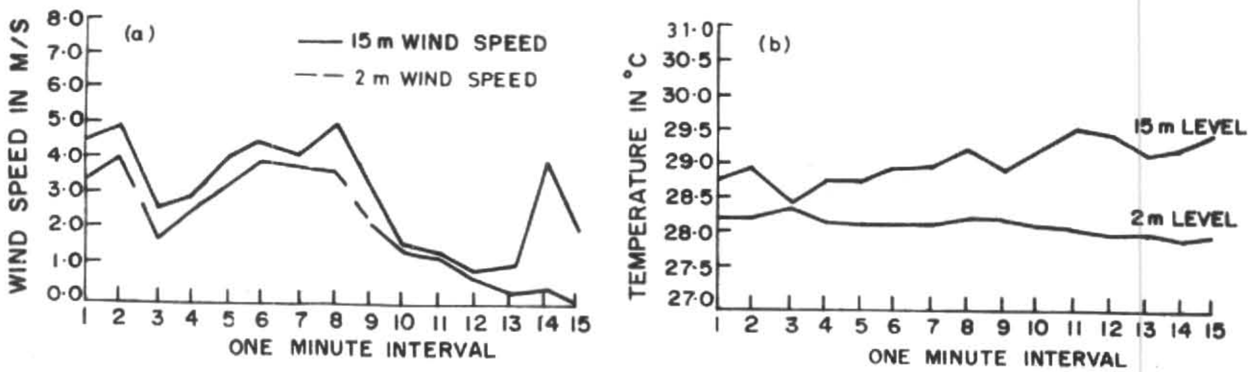
Fig. 6. Sensible heat flux by profile and aerodynamic method during 1330-1345 hrs (IST)

correlation method at levels 2 and 15 m from 1330 to 1345 hrs IST and 1430 to 1445 hrs IST respectively, while Fig. 6 represents transient nature of sensible heat flux by profile and aerodynamic methods from 1330 to 1345 hrs IST. Figs. 7 (a & b) show variation of wind speed and temperature at every minute from 1330 to 1345 hrs IST. Three independent techniques to estimate fluxes, were employed so that a firm conclusion with regard to stability and instability of surface layer can be drawn comparing with each other.

Fig. 1 shows sensible heat flux and Fig. 2 shows momentum and moisture fluxes during the period. First peak of sensible heat flux was found at the time of thunder and its value by aerodynamic method was 16.5 Wm^{-2} and the same by profile method was 23.2 Wm^{-2}. The momentum and moisture flux maxima reached at 0.41 Nm^{-2} and 3.8×10^{-5} kg m^{-2} s^{-1} respectively at the same time. Since Richardson number is a function of stability parameter, it decreased to -0.06 and there was corresponding increase in drag coefficient to 4.4×10^{-3} (Fig. 3). This inverse relationship between Richardson number and drag coefficient is also valid at 2030 IST.

Monsoon trough was north of its normal position on 27 July 1990, leading to convergence of wind and moisture along the trough zone and resulting in thundercloud and precipitation. First peak of average wind speed (6.8 mps) was found at 1230 hrs IST and then there was gradual decrease upto 1630 IST. Thereafter, there was a slight increase to 2.4 mps at 1730 IST. During 1730 to 2030 IST variation is insignificant. However, just after thunderstorm at 2030 IST there was rapid fall of wind speed. Similarly, there was gradual fall of temperature from 1230 to 1630 IST and sudden rise in temperature at 1730 IST. Thereafter, from 1830 to 2130 IST variation is less (Fig. 4). Cloud covers with precipitation modify diabatically the thermodynamic characteristics of sub cloud layer. When precipitation reaches the ground, precipitation-related evaporative cooling occurs (Fritsch *et al.* 1992), which directly brings change in the mesoscale mass field.

It was found that highest wind shear 0.61 mps was found at 1230 IST and thereafter gradual



Figs. 7 (a & b). Average (a) wind speed and (b) temperature on 27 July 1990 during 1330-1345 hrs (IST)

decrease was observed and at 1730 IST it was 0.29 mps further at 1830-2030 IST, *i.e.,* after second occurrence of thunderstorm it was maintaining its value of about 0.23 mps but wind speed was decreasing. It was found that beyond 2030 IST, wind speed as well as wind shear both are decreasing. No abrupt and significant change of moisture and momentum fluxes were noticed between 1730-2030 IST. However, sensible heat was found to be maximum at 1730 hrs and its value was obtained as 27.2 and 18.4 Wm^{-2} by profile and aerodynamic methods respectively. It is believed that this is because of the fact that maximum outgoing long wave radiation occurs during afternoon. Exchange processes in surface layer are enhanced by thunderstorm and decreased remarkably after its occurrence. The result indicates that in the evening there is continuous fall of sensible heat flux but there is sharp decrease of momentum and moisture fluxes after 2030 hrs. The decrease in sensible heat flux is substantially accounted by the absence of solar input to the ground after sunset.

We have also considered another case from non IOP period, on 3 July 1990 when there was a thunderstorm. Table 1 shows average sensible heat, momentum and moisture fluxes by profile and aerodynamic methods for that day at Varanasi. A low pressure area lay over southwest Uttar Pradesh and adjoining northwest Madhya Pradesh on that day. In addition to this, there was cyclonic circulation over Gangetic West Bengal and adjoining Bihar plateau extending upto mid-tropospheric level. At 1730 IST there was thunderstorm and sensible heat flux was computed as 18.4 Wm^{-2} by profile method and 13.2 Wm^{-2} by aerodynamic method while at 1430 IST there was rain without thunder and sensible heat was found to be 4.5 Wm^{-2} by profile method and 3.4 Wm^{-2} by aerodynamic method. Hence occurrence of thunderstorm increased the turbulence in the surface layer causing increase in wind speed and moisture flux.

TABLE 1

Time (IST)	Heat flux (Wm^{-2}) P	Heat flux (Wm^{-2}) A	Momentum flux (Nm^{-2})	Moisture flux ($kgm^{-2}s^{-1}$)	Wind speed (m/s)	Temperature (°C)
1430	4.5	3.4	0.075	1.43×10^{-5}	2.61	28.06
1730	18.4	13.2	0.123	2.18×10^{-5}	3.97	28.86

P — Profile method, A — Aerodynamic method.

One-minute mean of u', v', w' and T' are calculated and fluxes have been computed for each minute upto 15 minutes to study the stability of the layer. At 1330 IST, when surface layer in general was unstable, there was no contribution of sensible heat flux from level 2, but at level 5 there was uninterrupted upward transport of sensible heat. Maximum reached 40.0 Wm^{-2} at 8th minute of the observational period, which is shown in Fig. 5 (a). At the same time interval, maximum sensible heat flux has been computed to be 35.5 Wm^{-2} by profile method and 24.30 Wm^{-2} by aerodynamic method at 15 m height (Fig. 6). Fifteen minute averages from 1330 to 1345 IST is 16.9, 18.4 and 11.8 Wm^{-2} by profile, eddy correlation and aerodynamic methods respectively. Similary, at 2 m, values of average sensible heat flux by profile, eddy correlation and aerodynamic methods are -11.4, -10.2 and -7.4 Wm^{-2} respectively. Figs. 7 (a & b) show temporal variation of wind speed and temperatue from 1330-1345 IST.

At 2nd minute at level 2 there is a peak of wind speed 4.0 m/s but 2 m level temperature is always less than 15 m level. Therefore, downward flux was found at sonic level 2. By comparing 15 m and 30 m levels it was found that 30 m level temperature was always less than that of 15 m level and wind speed was always greater. Average temperature is 28.26°C at 2 m level, 29.25°C at 15m level and 28.46°C at 30 m level. In the similar way average wind speed is 2.28 m/s at 2 m level, 3.19 m/s at 15 m level and 4.65 m/s at 30 m level.

Thermal characteristics of different levels in the surface layer determine stable and unstable condition at a time. At 1430 IST, surface layer was in general stable. However, momentum and moisture fluxes are not completely supressed, because there was short burst of sensible heat flux from 6th to 10th minute of observational period reaching maximum upto 3.3 Wm^{-2} at level 2 and there are intermittent feeble short bursts at level 5 [Fig. 6 (b)]. In stable conditions, the turbulent fluxes may not only be discontinuous but also small and variable with height close to surface (Carson and Richards 1978). Average sensible heat flux was rated by profile, eddy correlation and aerodynamic methods as +1.22, 0.84 and 0.64 Wm^{-2} at 2 m level from 1430-1445 IST. Similarly, at 15m level it is −1.18, −0.59 and −0.50 Wm^{-2} by profile, eddy correlation and aerodynamic methods respectively. Comparative analysis indicates that the eddy correlation technique and profile method agree well for sensible heat flux.

5. Conclusions

The following conclusions could be drawn :

(*i*) Surface layer processes have been activated at the time of thunderstorm which lead to amplify the rate of transfer of fluxes upwards in the sub-cloud layer.

(*ii*) A systematic decrease in stability parameter before the thunderstorm makes the surface layer buoyant at the time of thunderstorm.

(*iii*) Study of surface layer in small vertical resolution is a complex phenomenon. However, our findings indicate that all the sub-layers are not unstable at a time inspite of the fact that lowest atmosphere is turbulent in general during a thunderstorm.

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