The dynamics of surface boundary layer during total Solar eclipse 1995

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सार — वायुमंडलीय परिसीमा स्तर (ए. बी. एल.) की गतिकीय पर खग्रास सूर्य ग्रहण के प्रभाव का अध्ययन करने के लिए रोबटर्सगंज (24° 42' उ., 83° 4' पू., 312 मी.ए.एम.एस.एल.) में 1.6 मीटर ऊँचा सूक्ष्म जलवायु वैज्ञानिक टावर बनाया गया जिसकी विभिन्न ऊँचाइयों पर पवन गति, तापमान और आर्द्रता संवेदी 6 उपकरणित बल्लियाँ लगाई गईं। इसके अलावा, इसी अवधि में मृदा तापमान और ऊष्मा अभिवाह को भी मापा गया। एक मिनट के औसत अंतराल पर प्रेक्षण लिए गए और डाटा लॉगर में लगातार रिकार्ड करते हुए इन्हें बाद के उपयोग के लिए पी.सी. पर अंतरित किया गया। 21 से 26 अक्तूबर 1995 तक के आंकड़े संग्रहित किए गए। ग्रहण की अवधि में सतह तापमान और मृदा तापमान में क्रमशः 6.2° सेल्सियस और 3.5° सेल्सियस की कमी तथा आर्द्रता में लगभग 60 प्रतिशत की वृद्धि का पता चला है। वेग के उतार चढ़ाव में कमी होने के कारण, अन्य दिनों की तुलना में पवन की औसत गति में तीव्र वृद्धि पाई गई। खग्रास सूर्य-ग्रहण से पहले वायुमंडल स्थिर रहा।

ABSTRACT. A microclimatological tower of 1.6 m height with six instrumented booms at different heights carrying wind speed, temperature and humidity sensors was set up at Robertsgunj (24°42'N, 83°4'E, 312m amsl) to study the implication of the total Solar eclipse on the dynamics of Atmospheric Boundary Layer (ABL). Apart from this, the soil temperature and heat flux were also measured during the same time. The observations were taken with a one minute average interval and recorded continuously with the data logger and then transferred to a PC for later use. The data were collected during 21 - 26 October 1995. During the eclipse period decrease of surface temperature and soil temperature by 6.2°C and 3.5°C respectively and increase of humidity by nearly 60% were observed. Due to the decrease in velocity fluctuations, the mean wind speed showed the sharp increase compared to other days. The setting of stable atmosphere before the total solar eclipse was observed.

Key words — Atmospheric Boundary Layer, Richardson Number, Sensible heat flux, Latent heat flux, Momentum flux, Friction velocity.

1. Introduction

The salient feature of Atmospheric Boundary Layer (ABL) over land is its diurnal variation. Following Sun rise, the boundary layer gets heated up leading to strong vertical mixing, driven rapidly and uniformly over the Earth's surface. ABL is characterised by turbulent motion that transports heat, momentum and moisture horizontally and vertically throughout the layer in accordance with the atmospheric conditions. The motion of air in the atmosphere and in particular, the ABL, is maintained as a direct consequence of solar radiation.

There is a well-known diurnal cycle in the ABL (Wyngaard, 1973). The corresponding day-night transitions are however the result of a gradual diminution in the solar radiation. In fact total solar eclipse provides a unique opportunity for a relatively clean ABL experiment, when the response of the layer to a sudden switching off of its major driving force may be observed, a situation that is otherwise so difficult to produce in nature. A solar eclipse may be considered as onset of night time condition on a compressed time scale. An ideal experiment to study the dynamics and the evolution of the ABL would be to study the variation in the boundary layer characteristics by decreasing and then increasing the solar radiation abruptly and slowly. A total solar eclipse provides the right setting for such an experiment due to complete cut off of the solar radiation, even a patch of clouds do not satisfy the required conditions due to complex reflection and scattering of light and constantly changing angles of the Sun to the Earth surface makes it very difficult to interpret the results.

The attempts comparable to the present experiment were made by Antonia *et al.* (1979) and Sethuraman (1982) who, reported some interesting measurements made during solar eclipses on 23 October 1976 and 16 February 1980 respectively. Unfortunately on both the occasions it was almost merged with the sunset period, so that the effect of the eclipse could not be unambiguously isolated, especially the results on the eclipse day were not compared with those on other days.

The present experiment aims to study the dynamics of the boundary layer, in particular, during eclipse period by calculating the flux values and other derived parameters like Richardson number, friction velocity, momentum flux. The values obtained on the eclipse day is compared with that of the previous and next day values.

2. Observation site

The experiment was conducted during 21 - 26 October, 1995 at Sant Kinaram College, 50 km from Varanasi (24°42′N, 83°4′E,312m amsl), which lies on the path of totality of the solar eclipse. The observational site was dry and flat land. The land was completely free from obstruction to the free flow of air. There were small buildings towards the south side at a distance of 200 m. The fetch to height ratio was more than 100.

Total solar eclipse started at 0727.49 hr (IST) on 24 October 1995 and the totality was between 0840.39 and 0841.48 hr (IST) *i.e.* there was a complete darkness for 69 sec. The eclipse ended at 1004.52 hr (IST).

3. Synoptic conditions over the site

With the passing of a western disturbance, there was cloudly to mainly overcast skies with intermittent drizzle on 21 October 1995. Later that day with the setting of westerly winds, the weather improved and remained partly cloudy to cloudy. In the late night the conditions improved from fair to fine weather. The condition of fine weather prevailed thereafter. The conditions experienced at Robertsgunj were ideal for a boundary layer experiment of this type due to constant fine weather condition that prevailed during the total eclipse period. Mainly the wind was from westerly direction with very light winds. The visibility remained good and the weather was mainly dry throughout the period.

4. Instrumentation

A microclimatological tower of 1.6 m height with six instrumented booms at different heights carrying wind, temperature and humidity sensors were set up to study the effect of the total solar eclipse on the surface layer. Soil temperature sensor and heat flux plates were exposed at the surface and sub surface level.

4.1. *Anemometer*

Cup anemometers (50 mm diameter) were mounted at the 20cm, 80cm and 160 cm. It is a 3 cup assembly, brass epoxy coated housing and stainless steel friction free shaft and coupled to a 22 hole chopper. Infrared light chopping (which cuts 22 times/revolution) arrangement was used to generate pulses which were then fed to a frequency to voltage conversion circuit so that direct calibration of wind speed *vs* voltage could be obtained. The pulse frequency is proportional to wind speed. The output is available in the voltage value.

4.2. *Humidity sensor*

The relative humidity was measured with the help of HMP 35A Humicap probe manufactured by Vaisala sensor systems. The humidity sensor is located at the tip of the probe and protected by the membrane filter. The probe with supply voltage of 7-35 v DC can be connected to the datalogger for continuous recording. The output voltage (0 to 100 mv) corresponds linearly to 0 - 100% of RH.

4.3. *Flux plate*

The heat flux at the surface was measured with the help of a HFT- 3 Soil Heat flux plate manufactured by M/s International Thermal Instruments Co, USA. It is a flat plate (38.56 mm diameter × 3.93 mm thick) transducer made of polymide glass. The upper and lower plates of the transducer are in thermal contact with a miniature thermopile. The thermopile is encapsulated in high thermal conductivity epoxy to prevent ground potential pickup. Its thermal conductivity is 0.906 W/m/K. The HFT has been used in the single ended measurements. When the plate is kept in contact with any surface the temperature difference across it produces a signal directly proportional to the heat flux. The signal output multiplied by the calibration factor, k (supplied by the manufacturer), gives the heat loss or gain from the surface directly. To avoid the radiative and convective errors the flux plate was exposed 5cm below the soil surface. For this sensor an output of 1 mv corresponds to 41.9 Watts/sq.m. A similar flux plate with an output of 1 mv corresponding to 42.7 Watts/sq.m was placed at the surface to monitor the variation of soil flux with respect to the surface wind.

4.4. *Air temperature & soil temperature*

Three terminal thermistor sensors (10 sec time constant) were procured from M/s Yellow Springs Instrument Co., USA. This thermilinear thermistor network is a composite device consisting of resistors and thermistors which produce an output voltage linear with temperature. These sensors can be operated in two ways: (*i*) resistor mode and (*ii*) voltage mode. In the present experiment, voltage mode was adopted. The sensors have been installed at 5,15,20,40,80 and 160 cm above ground level. For the measurement of soil temperature, a specially designed probe consisting of three sensors were exposed at the surface level, 10 cm and 20 cm below the ground.

4.5. *Data logger*

The data logger had 32 channels and the software provided, gives the integration of data ranging from one minute to one hour. In the present experiment the data series were recorded as one minute average, though the sampling was done for one per second for each parameter.

5. Data Analysis

The data were recorded on 16 channels comprising air temperature (six levels), wind speed (three levels), RH(two

levels), heat flux(two levels) and soil temperature (three levels).

For the evaluation of sensible and latent heat fluxes, profile technique (Businger *et al.* 1971, Oke, 1978) has been utilised. The profile method is based on the assumption that the turbulent fluxes of heat, moisture, momentum may be described by the product of a gradient of the transported quantity and some turbulent diffusivity K. This diffusivity is found by similarity theory providing the flux profile relation. The flux profile functions for stable and unstable conditions are empirically derived. For the calculation of latent heat flux, sensible heat flux, friction velocity, momentum flux, the available data have been averaged for 30 minute interval. The calculation of Q_H and Q_E was similar to that of Businger's (1971).

5.1. *Fluxes*

Sensible heat flux, latent heat flux, momentum flux and friction velocity have been evaluated from temperature and wind speed data measured at two levels *i.e.* 20 and 160 cm using the simplified profile method.

Sensible Heat Flux $QH = -\rho\ C_p\ k^2\ z^2\ (u/z.\ \theta/z)$

Latent Heat Flux $QE = -L_v\ k^2 z^2\ (u/z.\ \rho_v/z)$

where

ρ = air density in kg/m^3

C_p = Specific heat of air at constant pressure

k = von Karmann constant (0.4)

L_v = Latent heat of vapourisation

ρ_v = Absolute humidity

θ = $\theta_2 - \theta_1$ (Potential temperature at level 2-level 1)

u = $u_2 - u_1$ (Wind speed in m/s at level 2 - level 1)

z = $[(z_2-z_1)/\ln(z_2/z_1)]$

Under neutral condition, the relations for latent heat flux and sensible heat flux holds good. When the ABL becomes either unstable or stable, the quantity has to be combined with the dimensionless stability factor called $(\phi_m\phi_x)^{-1}$. Hence the relation becomes

$Q_H = -C_p k^2 z^2\ (u/z.\ \theta/z)\ (\phi_m\phi_H\ )^{-1}$

$Q_E = -L_v k^2 z^2 (u/z.v/z)\ (\phi_m\phi_v)^{-1}$

where,

ϕ_m = Dimensionless stability function of the logarithmic wind profile due to buoyancy effects

ϕ_H = Dimensionless stability function for heat

ϕ_v = Dimensionless stability function for humidity.

Observations suggests that $\phi_m = \phi_v = \phi_H$ in moderately stable conditions and $\phi_m = \phi_v = \phi_H^2$ in the unstable case.

Under stable conditions

$\phi_m = (1+5Ri)$

$\phi_v = (1-16Ri)^{-1/2}$

Under stable conditions

$\phi_m = (1+5Ri)$

$\phi_v = (1-16Ri)^{-1/4}$

where,

ϕ_m the appropriate stability function for the property being transferred.

Richardson number Ri = $(g/T)\ [(T_2-T_1)/(Z_2-Z_1)]/$
$[(u_2-u_1)/(Z_2-Z_1)^2]$

Apart from this friction velocity and momentum flux also been calculated for the same period using the following formula.

Friction Velocity $U^* = k[(u_2-u_1)/\ln(Z_2/Z_1)]$

Momentum Flux = $k^2\{(u_2-u_1)/\ [\ln(Z_2/Z_1)]\}^2$

6. Results and discussions

Figs.1(a-e) depicts the meteorological parameters *i.e.* wind speed, RH, air temperature, soil temperature and ground heat flux, averaged for 30 minutes and the duration between 0700-1900 hr (IST) on 23-25 October, 1995. For simplicity the figures show the value of one particular level on three different days. The figure covers the time duration of 0700-1900 hr. All the values are averaged for half an hour and represented in the figure. The Figs.1 (f-h) shows the derived parameters *i.e.* Richardson number, friction velocity and momentum flux respectively for the three days.

Figs.2(a-e) highlight the effect of meteorological parameters during the eclipse period *i.e.* 0700 - 1100 hrs (IST) on 24 October 1995. The curves depict the instantaneous value *i.e.* averaged for a minute . For the comparison purpose two or three level datas are represented. The calculated flux values on 24 - 25 October 1995 are shown in the Figs.2(f&g) respectively. The values were averaged for half an hour and covers the period between 0700-1900 hrs.

The variations in different meteorological parameters, before, during and after the eclipse period have been presented.

6.1. *Winds*

The most striking feature is the drop in wind speed during the eclipse period and maximum wind speed around noon after the eclipse been compared to all other days, as shown in the Fig.1(a). During totality the wind dies down to a dead calm especially during eclipse period this has been depicted in the Fig.2(a). The decrease in wind speed during eclipse period may be due to the suppression of turbulence due to the stabilisation of the surface layer following the drop in temperature. The steep increase in insolation, after eclipse, may be the reason for attaining the maximum wind speed on the eclipse day. Sharp increase in wind speed on the eclipse day results in the sharp increase in the friction velocity and momentum flux which are closely related with the wind speed. Similar results were also obtained by Anderson *et al.*, (1972).
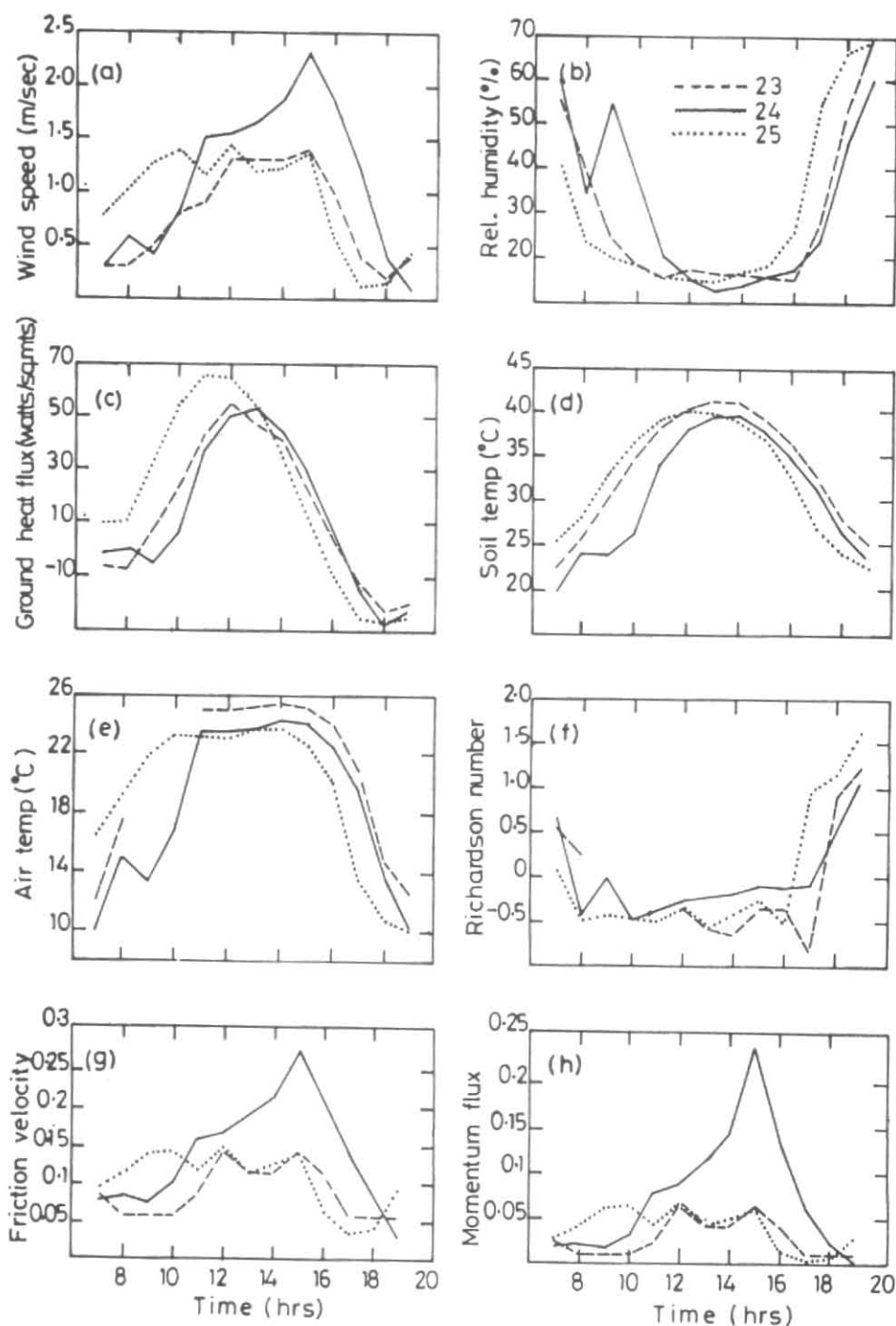
Figs.1(a-h). Meteorological parameters (a) Wind speed (b) Relative humidity (c) Ground heat flux (d) Soil temperature (e) Air temperature (f) Richardson number (g) Friction velocity and (h) Momentum flux averaged for 30 mins and for duration 0700 to 1900 hrs (IST) on 23-25 October 1995
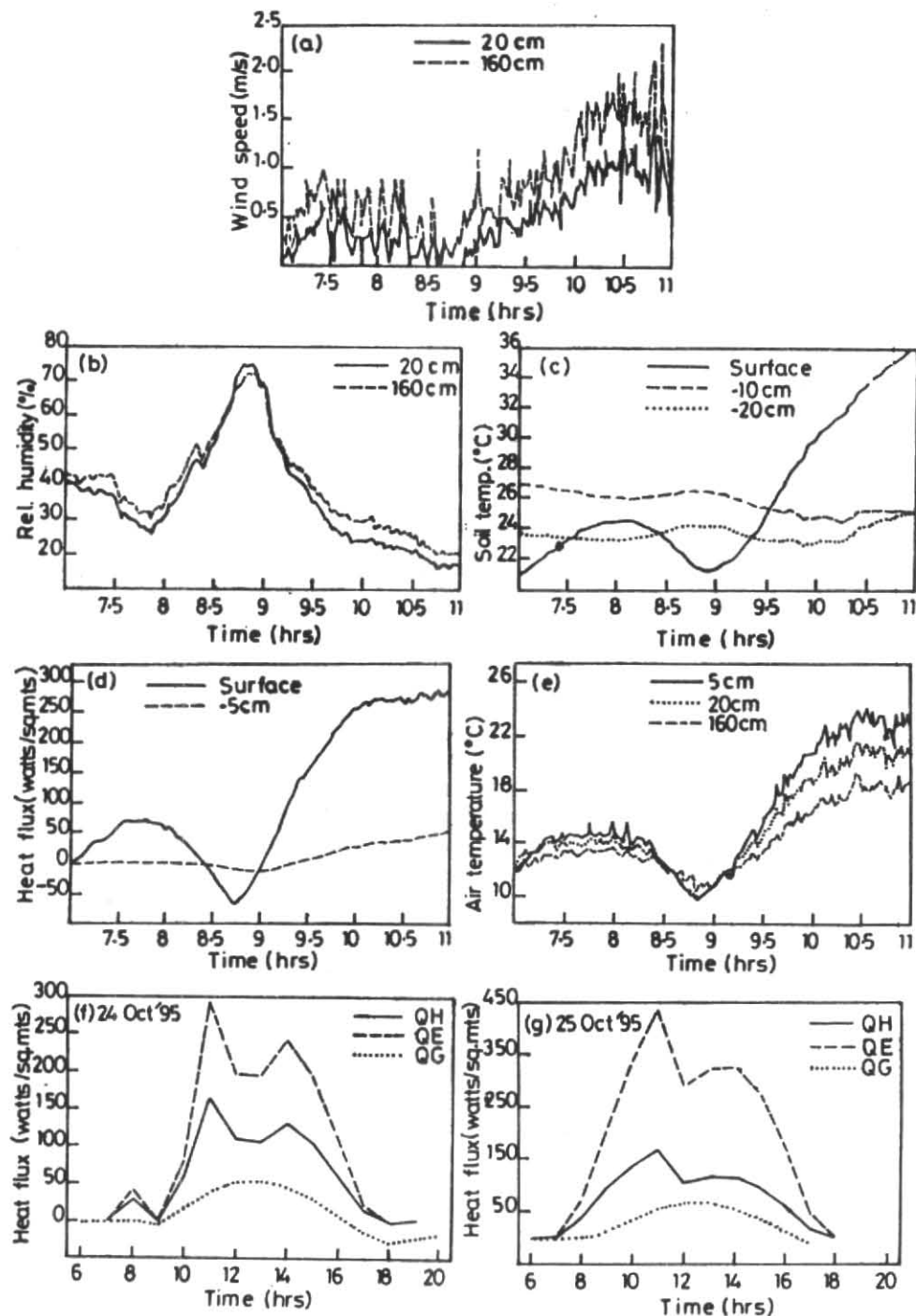
6.2. *Relative Humidity (RH)*

The diurnal variation of RH on all the three days (23,24 and 25) is depicted in the Fig.1(b). The humidity response to the atmosphere during the eclipse period has been highlighted in Fig.2(b). An increase of nearly 60% has been observed during the eclipse period. By taking the time derivative of the RH curve it is observed that RH increased at the rate of 3.3% and decreased at the rate of 6.5% later.

Due to the sharp decrease in RH, the value remained low as compared to other days. The value remained 15 to 35% above normal during the eclipse period and remained 5 to 20% below the normal after the eclipse hours.

6.3. *Soil temperature*

The soil temperature responds very slowly to the incoming radiation which is a well-known fact. The surface

Figs.2(a-g). Meteorological parameters (a) Wind speed (b) Relative humidity (c) Soil temperature (d) Heat flux and (e) Air temperature during the eclipse period from 0700 to 1100 hrs (IST) on 24 October 1995. Calculated heat flux values on (f) 24 October 1995 & (g) 25 October 1995 between 0700 & 1900 hrs (IST)

temperature showed maximum variation whereas the lower sub soil surfaces showed little variation. The response of the surface temperature is represented in Fig.1(d). The observations during the eclipse period showed the fall of temperature by 3.5°C at the surface and 1.3°C at 10 cm below after 50 minutes. While the temperatures at 20 cm below shows very little change of 0.7°C after 85 minutes. This has been

depicted in the Fig.2(c). The time derivative do not show much variation during the pre and post eclipse period.

6.4. *Heat flux*

The response of the surface heat flux and ground heat flux for the three days been depicted in the Fig.1(c). The surface heat flux and soil flux are inter connected and they have a direct linkage with the incoming radiation. The fluxes

decreased by about 90 watts/sq.m. during the eclipse time at the surface level and ground heat flux by 14 watts/sq.m. By taking the time derivatives of the flux curves, it is found that during eclipse, the surface heat flux falls at the rate of 1.1 watts/sq.m. Similarly the surface heat flux increased at the rate of 1.9 watts/sq.m after the eclipse period. This is depicted in the Fig.2(d). After the eclipse period the heat flux increased at the normal rate reaching a maximum value compared to those of other days.

The heat flux seems to propagate downwards when the solar radiation was diminished. This is probably related to the variations in the scales of the convective eddies due to the changes in the solar radiation received by the earth's surface. This feature is closely related to the evolution of the ABL.

6.5. Air temperature

The diurnal variation of air temperature at 5 cm agl for three days been depicted in the Fig.1(e). During the eclipse period the near surface level i.e. 5 cm, shows the fall of temperature of about 6.2°C, this range fairly agrees with the observed values during the previous solar eclipses. The temperature at the 160 cm also shows the fall of temperature of 3.2°C. The Fig.2(e) shows the response of the temperature at 5 cm, 20 cm and 160 cm agl. It may be noted that the atmospheric conditions are quite favourable for measuring the eclipse induced temperature changes. The sky was absolutely clear that the ambient temperature returned to within 0.5 to 1°C of its normal value after the eclipse. By taking the time derivative of the air temperature it has been observed that the rate at which the temperature fell at a rate of 1.4°C during the eclipse period and increased at a rate of 2.4°C after the eclipse period.

6.6. Friction velocity and momentum flux

Richardson number, friction velocity and momentum fluxes also been calculated for these days and shown in the Figs.1(f-h) respectively. Friction velocity and momentum flux curves for the three days 23-25 October 1995 shows that the eclipse day curve is distinct one. The 23 October and 25 October, 1995 the friction velocity curve and momentum flux curves are alike, but the eclipse day curve shows the sharp increase of the order of 4%. This sharp increase coincides with the maximum wind speed occurred around noon on the eclipse day.

6.7. Sensible and latent heat flux

Sensible and latent heat fluxes have been calculated for 24 - 25 October 1995. The latent heat flux shows the large variation compared to the next day. The latent heat flux on 24 October, 1995 has gone up by 150 watts/sq m compared to the eclipse day. Whereas the sensible heat flux shows very little variation, it is in the order of 10 watts/sq m. The ground heat flux also shows very little variation. It shows the fall of 10 watts/sq m compared to other days. The increase in the latent flux may be attributed to the increase in the RH by about 60%.

7. Conclusion

The solar eclipse of 24 October 1995 half an impact on the meteorological parameters. The net temperature, humidity, soil temperature, and heat flux showed a sharp difference on the eclipse day as compared to all other days. This type of data can be very useful for the modelling purpose. As the eclipse is a compressed form of nightfall, how the atmosphere behaves during the period of eclipse can be extended for the day scale.

Moreover the eclipse of 1980 occurred during the peak of solar activity which has a cycle of 11 years, but the eclipse of 1995 was during one of the solar minima. Hence the effect on meteorological parameters do not have a pronounced effect. Still the fall of surface temperature and soil temperature, increase in the amount of RH fairly agrees with the previous results (Antonia et al., 1979, Narasimha et al., 1982, Sethuraman, 1982) of total solar eclipse period.

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