CHAPTER 2

Land boundary layer characteristics

The thermal and dynamic interaction between the atmosphere and the underlying surface occurs through turbulent exchange of momentum, heat and moisture at their interface. The variation of fluxes of momentum heat and moisture in the surface boundary layer and their distribution in the rest of the planetary boundary layer play a vital role in the energy transport mechanism of the ocean-atmosphere land system. Over the Indian region the meteorological features exhibits wide variability during pre-monsoon, onset and post-monsoon periods. Also there is a region to region variation due to the topography of the region. Therefore the boundary layer characteristics over the region will also have wide variability spatially and during various seasons. Thus the boundary layer over the region during various periods requires special study. Several studies were done over the region giving special reference to the monsoon trough region using the MONTBLEX-90 data. All those studies bring out the variation in the surface layer parameters, structure of boundary layer etc., during the southwest monsoon period. The variations that occur in the boundary layer characteristics during various seasons were not examined well. It was also well known that the synoptic and mesoscale features and the atmospheric boundary layer have close linkage. Mishra and Salvekar (1980) produced unstable disturbances by explicit high-resolution integration of the boundary layer equations within the framework of quasi-geostrophic baroclinic theory. Shukla (1978) found CISK as an important mechanism for the instability during monsoon. These studies show the importance of boundary layer on the formation of disturbances. Only a very few studies are done so far to understand the variations in the characteristics in the boundary layer during synoptic scale or mesoscale disturbances (Pradhan et al 1994; Pradhan et al 1996; Singh 1992; Sivaramakrishnan et al 1996 etc.). These studies found that the surface flux increases steeply during development and intensification of the system and it decreases as it decays or passes away. The boundary layer variations that occur at different stations when a depression or cyclone is formed either over Bay of Bengal or over Arabian Sea was not investigated. All the earlier boundary layer studies associated with the cyclonic system were done as the system passes through the area of
study. According to Klinker (1997) in the tropics convection is an important process and the sensible heat flux shows a high correlation to convective rainfall. Hence deep convection may influence the surface fluxes. The interplay between thunderstorm and the boundary layer over the Indian region is not studied well by the earlier studies. Therefore in this chapter the variations in the boundary layer fluxes and stability during the pre-monsoon, onset and post-monsoon seasons at some selected stations over the subcontinent are examined. Also the variations in association with the formation of thunderstorms are also obtained. To understand the variations in boundary layer characteristics at different stations over the subcontinent during the formation of depressions or cyclones either over Bay of Bengal or over Arabian Sea the surface fluxes and stability parameter are computed at various stations during the occurrence of a monsoon depression.

Materials and Methods

The daily values of surface momentum, sensible heat and latent heat fluxes and stability parameter during April, May, June and October, November, December are obtained indirectly by the profile method for five years from 1984 to 1988 for three west coast stations Bombay, Mangalore and Trivandrum. Computations are performed using the daily surface observations of wind and temperature taken at 00UTC by the India Meteorological Department. The thunderstorm data and the associated rainfall in millimeters during the pre-monsoon and post-monsoon at Trivandrum are taken from the Indian Daily Weather Report to study the variations in surface layer characteristics during thunderstorms. The variations in surface layer features in association with the depression formed during August 2-6 over the Bay of Bengal at some selected stations are also obtained. The stations selected are (fig. (2.1)) Calcutta (CAL), Masulipatnam (MPT), Madras (MDS), Amini (AMN), Minicoy (MNC), Mangalore (MGL), Goa (GOA) and Bombay (BMB).

The surface fluxes of momentum can be obtained using the profile method which is an indirect method based mainly on Monin-Obukhov similarity theory. The wind profile, temperature profile and specific humidity profile in the surface layer can be described as (Dyer and Hicks 1970; Businger et al 1971)
Fig. 2.1 Track of Depression
\[ \Delta \bar{u} = \frac{(u_*/k)}{(\ln z_2/z_1 - \psi_m(\zeta))} \]  \hspace{1cm} (2.1)

\[ \Delta \bar{\theta} = \frac{(R\theta_*/k)}{(\ln z_2/z_1 - \psi_h(\zeta))} \]  \hspace{1cm} (2.2)

\[ \Delta \bar{q} = \frac{(Rq_*/k)}{(\ln z_2/z_1 - \psi_h(\zeta))} \]  \hspace{1cm} (2.3)

where \( \Delta u = u_2 - u_1 \) and \( u_2 \) are winds at levels 1 and 2 respectively, \( \Delta \theta = \theta_2 - \theta_1 \) is the difference in temperature at levels 1 and 2 respectively and \( \Delta q = q_2 - q_1 \) is the difference in specific humidity at levels 1 and 2 respectively. \( u_* \) is the frictional velocity, \( \theta_* \) is the temperature scale and \( q_* \) is the humidity scale, \( \psi_m \) and \( \psi_h \) are the stability functions associated with wind and temperature respectively. \( \zeta = z/L \) is the stability parameter, where \( z = z_2 - z_1 \) is the difference in height of the two levels 1 and 2. \( z_2 \) is taken at 10m height which is the height at which surface winds are measured and \( z_1 \) is the roughness length \( z_0 \) where \( u \) is zero. The roughness length is obtained following Delsol et al (1971) using the expression

\[ z_0 = 0.15 + 0.2(236.8 + 18.42h) \times 10^{-8} \]  \hspace{1cm} (2.4)

The temperature at the earth’s surface is obtained by solving the energy balance equation and that at 10m is obtained by linearly interpolating the observed surface temperature to that level.

The surface energy balance can be expressed as

\[ G_o = (1 - \alpha) S_w \downarrow + L_w \downarrow - \sigma T_s \uparrow - F_s \uparrow - F_l \uparrow \]  \hspace{1cm} (2.5)

where \( S_w \downarrow \) is incoming short wave radiation, \( L_w \downarrow \) is longwave radiation flux into the ground, \( \alpha \) the surface albedo which is taken as 0.15, \( \sigma T_s \) is the outgoing longwave radiation where \( \sigma \) is the Stefan-Boltzman constant. \( F_s \) and \( F_l \) are the fluxes of sensible and latent heat respectively which are obtained using stability dependent bulk aerodynamic formula and \( G_o \) is the soil moisture flux. The surface temperature is obtained by solving the equation using the software by Krishnamurty (1986). The first guess for \( T_s \) is assumed to be the air temperature at the lowest observation level. The data used for the computation of ground temperature is the upper air radiosonde data at
00UTC obtained from the India Meteorological Department. The saturated specific humidity at the surface is taken as the specific humidity at the surface. The computed ground temperature is compared with the NCEP reanalysis ground temperature data and both are found to be in good agreement.

$L$ is the Monin Obukhov length given by

$$L = \frac{T}{g} u^2 / g k_0$$

(2.6)

$R = 0.74$ is the ratio of eddy diffusivities in the neutral limit, $k = 0.4$, the Von Karman constant.

The stability functions can be written as (Paulsen 1970, Barker and Baxter 1975)

In the unstable condition ($\zeta < 0$)

$$\psi_m(\zeta) = \ln \left( \frac{1+x^2}{2} \right) + 2 \ln \left( \frac{1+x}{2} \right) - 2 \arctan x + \pi/2 \quad (2.7)$$

and

$$\psi_h(\zeta) = 2 \ln \left( \frac{1+y}{2} \right) \quad (2.8)$$

where $x = (1 - 15\zeta)^{1/4}$ and $y = (1 - 9\zeta)^{1/2}$

(2.9)

In stable condition ($\zeta > 0$)

$$\psi_m = -4.7\zeta \quad (2.10)$$

and

$$\psi_h = -4.7\zeta / R \quad (2.11)$$

The frictional velocity $u_*$, the temperature scale $\theta_*$ and humidity scale $q_*$ are computed iteratively. First a large value was assumed for $L$ and $u_*$ and $\theta_*$ are computed in neutral
limits. \( L \) is then recomputed using the computed \( u^* \) and \( \theta^* \) according to equation (2.6). Then \( u^* \) and \( \theta^* \) are recomputed using equation (2.1) and (2.2) with the new \( L \). Again \( L \) is recomputed with the recomputed \( u^* \) and \( \theta^* \) and this process is repeated until \( L \) does not change in desired accuracy limits.

The surface momentum flux is computed as
\[
\tau = \rho u^* \theta^* 
\]
(2.12)

Surface sensible heat flux is given by
\[
H = -\rho C_p u^* \theta^* 
\]
(2.13)

And surface latent heat flux can be expressed as
\[
E = -\rho L_e u^* q^* 
\]
(2.14)

where \( \rho \) is the density of air which does not have much variation in the layer considered and is taken as \( 1.25 \times 10^3 \text{kgm}^{-3} \), \( C_p \) is the coefficient of specific heat capacity at constant pressure and \( L_e \) is the latent heat of evaporation/condensation.

Results and discussion

Variation in surface fluxes during pre-monsoon, onset and post-monsoon periods

a) Momentum flux

The surface momentum flux during April, May and June for five years from 1984-1988 at Bombay, Mangalore and Trivandrum are given in figures (2.1a-2.1c) respectively. The momentum flux is much less during April and May when compared to that during June at Bombay. During the pre-monsoon period the flux remains almost constant throughout the period with occasional rise in value. But as the monsoon is reached the surface momentum flux increases and the values reach \( 0.2 \text{Nm}^{-2} \) and occasionally more. At Mangalore the momentum flux is less than \( 0.2 \text{Nm}^{-2} \) during most of the days in April and early May. Occasional increase in flux is noticed during the period. But by late May and June the flux increases and is about \( 0.2 \text{Nm}^{-2} \) or more during
Fig. 2.1a Momentum flux during April, May and June 1984 - 1988 at Bombay

Fig. 2.1b Momentum flux during April, May and June 1984 -1988 at Mangalore
Fig. 2.1c Momentum flux during April, May and June 1984 - 1988 at Trivandrum

Fig. 2.2a Momentum flux during Oct.-Dec. 1984 - 1988 at Bombay
most of the days. At Trivandrum high flux is noticed in most of the days much before the onset of monsoon and very high flux transport occurs after the monsoon is reached over the station in June. Comparing the magnitudes of the surface momentum flux at the three stations, high flux values are noticed at Trivandrum. Mangalore is having higher fluxes when compared to that at Bombay. Therefore as the monsoon flow approaches the station there is an increase in surface momentum flux. The increase is due to the increase in surface winds in association with the monsoon onset. The observed wind speed at Trivandrum is higher than the other two stations hence higher fluxes are noticed at the station.

Surface momentum flux during October, November and December for five years from 1984-1988 at Bombay, Mangalore and Trivandrum are shown in figures (2.2a-2.2c) respectively. The surface flux was much smaller during October and it increased in most of the days during November and December at Bombay. The increase was in association with the increase in the northeastern wind speed. The maximum flux values are found to be less than 0.2Nm$^{-2}$ mostly. At Mangalore the surface flux remained less than 0.2Nm$^{-2}$ in October which increased during November and December and reached even up to 0.6Nm$^{-2}$ or more occasionally. At Trivandrum higher surface momentum flux was noticed during October. High fluxes are also noticed during certain days in November. The momentum flux in general is having a decreasing trend from October to December at Trivandrum. High flux during October is due to the high wind speeds in association with the withdrawal of southwest monsoon from the subcontinent. Also during the post-monsoon period cyclonic systems will form over Bay of Bengal or Arabian Sea which causes an increase in wind speed. Therefore surface momentum flux will be higher during the occurrence of these systems.

Comparing the flux values during the various periods higher values are noticed during the pre-monsoon and onset periods than the post-monsoon period at all the three stations. This is due to higher wind speed during the pre-monsoon and onset than during post-monsoon. High winds blows across Arabian Sea into the subcontinent much before the onset of monsoon. Because of this high winds higher fluxes are noticed during the period. The northeasterly winds are not much stronger as the monsoon winds at the three west-coast stations considered.
Fig. 2.2b Momentum flux during Oct.- Dec. 1984 -1988 at Mangalore

Fig. 2.2c Momentum flux during Oct.- Dec.1984 - 1988 at Trivandrum
b) Sensible heat flux

The time series of surface sensible heat flux during April, May and June from 1984-1988 at Bombay, Mangalore and Trivandrum are given in figures (2.3a to 2.3c) respectively. At Bombay very high sensible heat flux was noticed during April which decreased by May. The fluxes reached even more than 300Wm$^{-2}$ in certain days in April. In May it was less than 200Wm$^{-2}$. It then increased during the onset period. High flux during April is due to the high temperature in the surface layer whereas the increase in June is in association with the increase in wind speed during the onset. At Mangalore the sensible heat flux remains between 100-200Wm$^{-2}$ during the pre-monsoon period with occasional rise to about 300Wm$^{-2}$. The flux increased by the onset and is found to be greater than 200Wm$^{-2}$ in most of the days. Very high sensible heat flux occurs in certain days during pre-monsoon period and onset period at Trivandrum. It even reached up to 300 Wm$^{-2}$ or more. High flux during the pre-monsoon is due to the high temperature during the period whereas at the time of onset the high wind speed contributes towards the increase in flux.

Figures (2.4a to 2.4c) show the time series of sensible heat flux during October, November and December from 1984-1988 at Bombay, Mangalore and Trivandrum respectively. The sensible heat flux was much less during October at Bombay and it increased gradually and very high fluxes are noticed during December. It was found to reach even up to 600Wm$^{-2}$ or more. At Mangalore also the sensible heat flux gradually increased from October to December. During October the flux was less than 200Wm$^{-2}$ which gradually increased in November and December. Higher flux values of about 400Wm$^{-2}$ are noticed in certain days. At Trivandrum the sensible heat flux is found to be between 100–200Wm$^{-2}$ most of the days throughout the period. In certain days the flux increased and reached even more than 300Wm$^{-2}$. Higher sensible heat flux is noticed at Bombay when compared to the fluxes at Mangalore and Trivandrum. The lesser values during October may be due to the radiative cooling of the surface layer because of the overcast skies during the withdrawal period. After that the fluxes increase due to increase in temperature in surface layer during the period. The flux values are found to be very high but Pradhan et al (1994) has reported high sensible heat flux greater 350Wm$^{-2}$ at Kharagpur during MONTBLEX-90.
Fig. 2.3a Sensible heat flux during April, May and June 1984 - 1988 at Bombay

Fig. 2.3b Sensible heat flux during April, May and June 1984 - 1988 at Mangalore
Fig. 2.3c Sensible heat flux during April, May and June 1984 -1988 at Trivandrum

Fig. 2.4a Sensible heat flux during Oct. - Dec. 1984 - 1988 at Bombay
Fig. 2.4b Sensible heat flux during Oct.-Dec. 1984-1988 at Mangalore

Fig. 2.4c Sensible heat flux during Oct.-Dec. 1984-1988 at Trivandrum
c) Latent heat flux

The time series of latent heat fluxes at Bombay, Mangalore and Trivandrum during April to June, 1984-1988 is given in figures (2.5a to 2.5c) respectively. The latent heat flux during the period at Bombay was found to be between 250-500 Wm\(^{-2}\) with occasional rise. In certain days the flux values were less than 250Wm\(^{-2}\) and downward flux was noticed occasionally. Higher fluxes are noticed during late May and June, which is during the onset of southwest monsoon. At Mangalore the latent heat fluxes during April and May remain more or less constant and the range is found to be around 300-400Wm\(^{-2}\). By monsoon onset high fluxes are noticed at the station and it may reach up to 650Wm\(^{-2}\). At Trivandrum very high fluxes are noticed in certain days during the pre-monsoon months. By the monsoon onset the fluxes are very high. The flux may reach up to 750Wm\(^{-2}\). The higher fluxes are due to increase in wind speed during the period in association with the onset. Higher fluxes are noticed at Trivandrum when compared to Bombay and Mangalore. This is because of the high-speed winds at the station. The surface latent heat flux is generally higher during the onset period.

Figures (2.6a to 2.6c) shows the time series of latent heat fluxes during October, November and December, from 1984-1988 at Bombay, Mangalore and Trivandrum respectively. At Bombay during the post-monsoon periods higher fluxes are noticed during October. After that the fluxes decreased and downward fluxes were noticed in certain days. Very high fluxes are noticed occasionally which may be due to the occurrence of disturbances. At Mangalore during October the flux remained almost constant, which was about 300-400Wm\(^{-2}\). After that lesser flux values are noticed and downward flux transport occurs in certain days during November and December. At Trivandrum higher fluxes were noticed during the month of October. After that during November and December it remained almost constant and is found to be around 300Wm\(^{-2}\). In certain days very high fluxes are noticed which is due to the disturbances during the period. Therefore in the post-monsoon periods the latent heat flux is found to decrease from October to December. Higher fluxes during October are due to the higher winds and rainfall activity in association with the withdrawal of southwest monsoon. After October the rainfall activity is very less therefore there will be less moisture.
Fig. 2.5a Latent heat flux during April, May and June 1984 - 1988 at Bombay

Fig. 2.5b Latent heat flux during April, May and June 1984 - 1988 at Mangalore
Fig. 2.5c Latent heat flux during April, May and June 1984 - 1988 at Trivandrum

Fig. 2.6a Latent heat flux during Oct.-Dec. 1984 - 1988 at Bombay
Fig. 2.6b Latent heat flux during Oct.- Dec. 1984-1988 at Mangalore

Fig. 2.6c Latent heat flux during Oct.- Dec. 1984-1988 at Trivandrum
available at the surface for evaporation hence lesser values and downward transport is noticed. The sensible heat flux is found to increase at Bombay and Mangalore during the post-monsoon period whereas the latent heat flux is decreased. But during the onset period at all the three stations the sensible heat and latent heat fluxes increase. This shows that the monsoon activity influences the surface boundary layer characteristics by increasing the surface fluxes.

**Surface stability parameter during pre-monsoon, onset and post-monsoon periods**

Figures (2.7a to 2.7c) shows the variation of stability parameter during April, May and June from 1984-1988 at Bombay, Mangalore and Trivandrum. The stability parameter indicates that at Bombay the atmosphere tends to attain near neutral or less unstable condition during June by the monsoon onset. The surface layer which was highly unstable during April gradually tends to become less unstable in May and reaches near neutral condition in June. At Mangalore the stability parameter is highly fluctuating between unstable and neutral situations during the period. But by monsoon onset the atmosphere is in near neutral condition. At Trivandrum the atmosphere reaches near neutral condition most of the days in April and May. This may be due to the presence of moist winds during the period. In June the atmosphere is in near neutral condition throughout the period.

The time series of stability parameter during October, November and December 1984-1988 at Bombay, Mangalore and Trivandrum are given in figures (2.8a to 2.8c) respectively. At Bombay the atmosphere which was less unstable during October becomes more unstable in most of the days during December. That is the atmosphere tends to become highly unstable in most of the days during December from the less unstable situation in October. As soon as it becomes highly unstable the atmosphere tries to attain neutrality or less unstable situation. At Mangalore the surface layer during the period fluctuates between highly unstable and less unstable condition. At Trivandrum in early October the atmosphere was in near neutral condition. After that the atmospheric condition is fluctuating between the highly unstable and less unstable conditions. That is during November and December the atmosphere is highly unstable and it always tends to less unstable situation from highly unstable by increasing the turbulence in the boundary layer. But in October which is the withdrawal period of monsoon the atmosphere is less
Fig. 2.7a Stability parameter during April-June 1984 - 1988 at Bombay

Fig. 2.7b Stability parameter during April-June 1984 - 1988 at Mangalore
Fig. 2.7c Stability parameter during April-June 1984 - 1988 at Trivandrum

Fig. 2.8a Stability parameter during Oct.-Dec. 1984 - 1988 at Bombay
Fig. 2.8b Stability parameter during Oct.-Dec. 1984 -1988 at Mangalore

Fig. 2.8c Stability parameter during Oct.-Dec.1984 - 1988 at Trivandrum
unstable or in near neutral condition. Thus the activity of the monsoon has got profound influence on the surface layer stability. Therefore all the activities in the surface layer, particularly the exchange processes do get influenced by monsoon activity.

In general at the three stations considered the surface layer becomes less unstable or near neutral by the onset of monsoon. This is because of the presence of moist winds and radiative cooling of the surface layer due to overcast sky during onset period. The less unstable situation during October is also because of the moist winds and radiative cooling of the surface during the withdrawal period of monsoon. During the pre-monsoon and post-monsoon months when usually clear sky conditions prevail the atmosphere becomes highly unstable. Whenever the atmosphere becomes highly unstable it soon tries to attain less unstable situation. This is achieved by increasing the turbulence and therefore the turbulent fluxes. When the atmosphere becomes highly unstable the surface turbulence increases and the turbulent fluxes are increased so that the atmosphere attains less unstable condition. High fluxes are noticed soon after the atmosphere is highly unstable so that less unstable situation is attained.

**Surface layer characteristics during the occurrence of thunderstorms**

Variations in surface fluxes and surface stability during the occurrence of thunderstorms in the pre-monsoon and post-monsoon months at Trivandrum are shown in figures (2.9a to 2.9f). During the pre-monsoon period the frequencies of thunderstorm are more in the month of April whereas during the post-monsoon season the October and November months give more thunderstorms. The stability parameter shows highly unstable situation in the atmosphere before the occurrence of thunderstorm and it attains less unstable or near neutral condition soon after the occurrence of the thunderstorm. In April during the occurrence of thunderstorms the stability parameter is found to be fluctuating between highly unstable and less unstable situations. The atmosphere becomes less unstable or near neutral after the thunderstorm. This may be due to the radiative cooling of the ground and presence of moist winds after the rainfall from thunderstorms.
Fig. 2.9a Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during April 1984

Fig. 2.9b Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during April 1985
Fig. 2.9c Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during April 1986.

Fig. 2.9d Stability parameter, surface fluxes, rainfall associated with thunderstorms at Trivandrum during April 1987.
Fig. 2.9e Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during April 1988

Fig. 2.9f Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during Oct. - Nov. 1984
Fig. 2.9g Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during Oct.-Nov. 1985

Fig. 2.9h Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during Oct.-Nov. 1986
Fig. 2.9i Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during Oct.-Nov. 1987

Fig. 2.9j Stability parameter, surface fluxes and rainfall associated with thunderstorms at Trivandrum during Oct.-Nov. 1988
In the post-monsoon period most of the thunderstorm activity is during October and November. During these months also the atmospheric stability condition fluctuates between highly unstable and less unstable after the thunderstorm activity. Before the thunderstorm the atmosphere becomes highly unstable and becomes less unstable soon after the thunderstorm activity. Therefore the stability parameter in the atmospheric surface layer gives a clear indication of occurrence of thunderstorms much before its activity occurs in the atmosphere. The thunderstorm activity very much influences the surface layer stability, hence the energy exchange processes in the surface layer also gets affected by it.

The surface layer momentum, sensible heat and latent heat flux shows an increase in association with the occurrence of thunderstorms. As soon as the atmosphere becomes highly unstable prior to the occurrence of thunderstorm the surface turbulence increases and the surface turbulent fluxes are increased so that the atmospheric flow becomes less unstable. During the pre-monsoon period the momentum flux is found to reach 0.6Nm$^{-2}$ and occasionally more than that. The surface sensible heat flux reached a maximum of 300Wm$^{-2}$ and in certain days higher values are noticed. The latent heat flux is found to be slightly higher in magnitude in certain days which was found to be about 800Wm$^{-2}$. During the post-monsoon period the surface momentum flux was found to be 0.4Nm$^{-2}$ and occasionally higher. The surface sensible heat flux was found to be less than 300Wm$^{-2}$ and downward flux was noticed as the atmosphere becomes highly stable. The latent heat was found to reach a maximum of 600Wm$^{-2}$ and sometimes higher. Therefore the thunderstorm activity influences the surface layer exchange properties. The surface fluxes were high during the occurrence of thunderstorms and because of the radiative cooling of the surface due to intense rainfall activity the atmosphere becomes neutral or stable. The convection in association with the thunderstorms increases the surface turbulence and hence the surface fluxes.

**Surface layer characteristics during the occurrence of monsoon depression**

Surface layer stability parameter and surface fluxes over various stations are computed during the life period of the depression (August 2- August 6) formed over Bay of Bengal in 1988. The track of the depression is shown in figure (2.1). The stations selected are also given in the figure. The depression was formed over the head Bay on
August 2\textsuperscript{nd} and crossed West Bengal coast near Calcutta on the same day evening. The surface layer characteristics at Calcutta are given in figure (2.10a). The stability parameter shows unstable condition on August 1, which attained less unstable or near neutral condition by August 2. Near neutral condition prevailed in the atmosphere till August 3\textsuperscript{rd} and became highly unstable at 1200 UTC on August 4 and then it fluctuated between highly unstable and less unstable condition. The atmosphere was found to be highly unstable prior to the formation of depression and it soon became less unstable as the system reached the station. The less unstable situation is reached as a result of cooling of the surface due to overcast skies and moist winds due intense rainfall activity during the period. As the effect of the system was decreased over the station the atmosphere returned to highly unstable condition and is found to transit between unstable and less unstable situation. The momentum flux was found to increase from August 1\textsuperscript{st} and reached maximum on August 2\textsuperscript{nd} and 3\textsuperscript{rd} and then decreased. The flux was found to increase as the system is near the station after that it decreased and increased at 12 UTC on August 5\textsuperscript{th}. The surface layer is highly unstable on August 5\textsuperscript{th} at 00 UTC and due to this surface turbulence increases and the turbulent exchange increases so that higher fluxes are noticed soon after. The surface latent heat and sensible heat fluxes also shows similar trend. A decrease in fluxes was noticed on August 2\textsuperscript{nd} and it increased as the system crosses land. The decrease was as a result of the radiative cooling of the ground due to overcast skies and presence of moisture as a result of the rainfall from the system. The atmospheric condition on the day was almost neutral. The latent heat flux decreases on August 4\textsuperscript{th} after the effect of the system over the station decreased. An increase was noticed further in association with the instability in the atmosphere. The fluxes were found to be slightly higher in magnitude, which might be due to the error occurred in the radiosonde observation during the period. The sensible heat flux decreases on August 3\textsuperscript{rd} due to radiative cooling of the surface layer as a result of the overcast skies. Then it increases on August 5\textsuperscript{th} due to increase in turbulence as a result of high instability in the atmosphere. At Masulipatnam (fig.2.10b) which is an east coast station the effect of the depression is noticed in the surface layer characteristics. The atmosphere, which was unstable on July 31\textsuperscript{st} and at 00 UTC on August 1\textsuperscript{st} became less unstable and remained so on till August 2\textsuperscript{nd}. After that it fluctuated between highly unstable and less unstable situation. High instability was noticed on August 4\textsuperscript{th} at 12 UTC. As soon as the atmosphere becomes highly unstable it tries to attain less unstable situation by increasing the surface turbulence and hence the surface fluxes. Increase in surface fluxes was
Fig. 2.10a Stability parameter and surface fluxes at Calcutta (Jul. 31- Aug. 7 1988)

Fig. 2.10b Surface fluxes and stability parameter at Masulipatnam (Jul. 31-Aug 7. 1988)
noticed soon after the atmosphere is highly unstable. The increase is due to strong winds during the disturbance. At Madras also high instability is noticed on July 31st before the formation of the depression (fig.2.10c). The atmosphere becomes less unstable during August 1-3 after which it again becomes highly unstable and transits between highly unstable and less unstable condition. The less unstable situation during the occurrence of depression is achieved as a result of the radiative cooling of the surface due to overcast skies and moist winds. The surface momentum, sensible heat and latent heat fluxes are higher during the system. Higher fluxes are noticed soon after the atmosphere becomes highly unstable. At Amini and Minicoy (figures 2.10d and 2.10e) the atmospheric condition fluctuates between highly unstable and less unstable situation during the disturbance and becomes highly unstable after the decay of the disturbance. Higher surface fluxes are noticed throughout the period at the two stations. At Mangalore (fig.2.10f) the atmosphere is in near neutral condition during the life period of the depression and becomes highly unstable after August 5th. Near neutral condition is due to overcast skies and moist winds due to the disturbance. After the effect of the depression decreases the atmosphere becomes highly unstable. The surface momentum, sensible and latent heat fluxes are very high during August 2-5 after which it decreases. The high-speed winds during the period are responsible for the increase in surface fluxes. At Goa the atmosphere is highly unstable prior to the formation of the depression and becomes near neutral or stable during the disturbance and becomes unstable again on August 5th (fig.2.10g). The surface fluxes are much higher during the period. Downward flux was noticed in latent heat flux on August 2nd and 6th. Downward sensible heat flux occurs over the station during the period as a result of the high stable condition reached in the atmosphere. At Bombay (fig.2.10h) the atmosphere was highly stable on July 31st which gradually became unstable on August 2nd. It was in near neutral condition during August 2-5 due to the depression. After that the atmospheric condition fluctuates between highly unstable and less unstable condition. There was a decrease in surface flux during July 31st and downward sensible heat flux was noticed on the day. This was due to the highly stable condition of the atmosphere on July 31st. After that the surface fluxes increases and higher fluxes are noticed during August 1-4.

The atmosphere therefore becomes highly unstable much before the disturbance and it attains near neutral situation or less unstable situation during the life period of the disturbance due to radiative cooling of the ground because of highly overcast skies and
Fig. 2.10c Stability parameter and surface fluxes at Madras (Jul. 31-Aug. 7 1988)

Fig. 2.10d Stability parameter and surface fluxes at Amini (Jul 31-Aug 7 1988)
Fig. 2.10e Stability parameter and surface fluxes at Minicoy (Jul. 31 - Aug. 7 1988)

Fig. 2.10f Stability parameter and surface fluxes at Mangalore (Aug. 1-7 1988)
Fig. 2.10g Stability parameter and surface fluxes at Goa (Jul. 31-Aug. 7 1988)

Fig. 2.10h Stability parameter and surface fluxes at Bombay (Jul. 31-Aug. 7 1998)
moist winds. This feature is noticed at all the stations considered. As the system decays or the effect gets reduced the atmosphere returns to highly unstable situation from the less unstable condition and transits between highly and less unstable conditions. Higher flux transport occurs during the depression period. Sivaramakrishnan et al (1996) and Murty et al (1996) noticed an increase in surface flux over the oceanic surface during the passage of a depression over the region. Therefore the surface layer features respond to the synoptic scale variations due to the depression formed over the head Bay and which moved over the subcontinent through a track along the monsoon trough. The disturbance is found to have an impact on the surface layer features not only near the region of its formation and along its path but also on the entire subcontinent.

Therefore the surface layer characteristic is found to vary during various seasons. Higher fluxes are noticed during the monsoon onset period due to increase in wind speed during the period. The stability condition shows near neutral or less unstable condition as the monsoon reaches a station. During the pre-monsoon and post-monsoon period the atmospheric condition is mostly unstable. The surface layer tends to become less unstable from the highly unstable condition by the onset and vice versa after the withdrawal of monsoon. The synoptic scale and mesoscale features and the surface layer characteristics are found to have close relation. An increase in surface fluxes is noticed during the occurrence of these disturbances. The surface layer is found to become highly unstable prior to the occurrence of these disturbances thus giving a prior indication of their formation. The occurrence of the synoptic scale disturbance affects the surface layer characteristics on the entire subcontinent as soon as it is formed.