CHAPTER 2

SURFACE BOUNDARY LAYER CHARACTERISTICS OVER COCHIN
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2.1 Introduction

The lowest part of the Atmospheric Boundary Layer (ABL) is called surface layer. Usually 10 per cent of the total height of the ABL is taken as the height of surface layer. The typical height of the surface layer is 100 m during daytime and less than that during night time (Oke, 1978). The variation of the surface fluxes in the surface boundary layer with height is less (not more than 10 %) so that this layer also called constant flux layer (Haugen et al., 1971, Hogstorm, 1988). The variation of fluxes of momentum and heat in 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-land-atmosphere system. The primary mechanism for these processes is mainly affected by the turbulence. The turbulence in this layer caused mainly due to the wind shear, which is generated by the surface frictional force known as mechanical turbulence (Arya, 1988).

Thermal and dynamic interaction between the atmosphere and underlying surface occur through the turbulent exchange of momentum, heat and moisture at their interface. Over the Indian region the meteorological features exhibit a wide variability during different seasons. Several studies were carried out over the region with special emphasis to the monsoon trough region using the MONTBLEX-90 data set (MONTBLEX REF). All those studies bring out the variation in the surface layer parameters, structure of the boundary layer etc. during the southwest monsoon period. In the tropics, convection is important and the sensible heat flux shows high correlation with convection rainfall, hence deep convection may influence surface fluxes.

The most striking feature associated with the ABL is the land sea transition with flow perpendicular to the coast in the coastal stations. The characteristic features such as sea breeze and land breeze circulations in the coastal areas have considerable attention because the coastal areas are densely populated, dispersion of pollutants from various industries and other anthropogenic activities depend in the coastal
boundary layer. Pollutants emitted near the shore can remain confined in stagnant condition for a long time in a closed sea breeze cell (Keen and Lyons, 1978; Ozoe et al., 1983). The coastal ABL zone is a transition zone in which airflow constantly adjusts to the new boundary conditions when it crosses the shoreline.

The sea breeze is a mesoscale circulation and also a thermally direct circulation that arises from the differential heating along the land-sea interface and it is due to the difference in heat capacity and molecular conductivity of land and sea. The land and sea breezes are locally induced lower atmospheric mesoscale circulation and occur everywhere in the coastal belt. The other type of circulations formed due to the differential heating are lake breezes, land breezes and inland breezes (Bechtold, et al., 1991), snow breezes (Segal et al., 1991), fog breezes and breezes formed by difference in cloud cover. In tropical and subtropical areas the sea breeze are very regular, occurring almost daily (Simpson, 1994). It has been well established that as cool and stable air over water bodies crosses the shore line and advected over a heated land mass, a temperature inversion is formed over land which gradually slops up as function of distance (Kunhikrishnan et al. 1993) from the shore line (fetch distance). In both coastal and inland areas sea breeze phenomena play an important role in the transport of air pollutants by forming characteristic meteorological situations (Kimura, 1983). Sea breeze has a very crucial role in dispersing pollutants from the source region and features of such local circulation is important for aviation safety, sailing and forest fire forecasting.

Sea breeze circulation has a vertical extent of about 2 km and horizontal extent of about 50 km. In order to satisfy the mass continuity, there is a return flow from land to sea in the upper level during the sea breeze and vice versa. The sea breeze study is important in view of onset and cessation time, maximum intensity, vertical and horizontal extension etc. Theoretical aspects of sea breeze circulation were studied extensively by Pearson (1973), Rutunno (1983) and Dalu and Pielke (1989). They introduced characteristic time scale for sea breeze circulation and identified the importance of friction in the intensity and horizontal extension of sea breeze. Aircraft measurements were used for studying sea breeze features by Fisher (1960). After analyzing data over Trivandrum for 392 days (spread over three years), Narayanan (1967) reported that sudden onset of sea breeze is usually accompanied by a rise in humidity, shift in wind direction and increase in wind speed. Nakane and Sasano
(1986) used high-resolution measurements with the help of a Lidar to study sea breeze events. Yoshikado (1990) used soundings for the observational studies on sea breeze. Other observational studies on horizontal structure of sea breeze circulation carried out by Wakimoto and Atkins (1994) and Atkins and Wakimoto (1997). They found that the gradient of temperature and moisture structure during sea breeze passage were strongest and weakest during offshore and onshore flow days respectively. Sha et al (1991) showed that inland penetration of sea breeze slows down in the after noon due to Kelvin-Helmholtz instabilities on the transition from the sea breeze layer to the return current layer. Kusaka et al (2000) established from the simulations that land-use alteration modified the wind system and the time required for the sea breeze to reach inland areas increased by two hours. Sea breeze characteristics over Kalpakam, a tropical site is studied using mesoscale model by Jamima and Lakshminarasimhan (2004) and they found that the sea breeze duration is about 6 hours and the model also agrees with observation. Ohashi and Kida (2001) observed that sea breeze circulation penetrating from Osaka Bay to the inland Kyoto basin, weak wind region (wind speed of less than 2 ms$^{-1}$) of greater than 1000 m in height was found just ahead of the inland moving a sea breeze front. Kitada (1987) studied to predict the dynamical behavior of eddy diffusivity, turbulent kinetic energy and its dissipation rate associated with moving sea breeze front.

A good amount of work has been carried out by different investigators to understand the climatological as well as the general studies on sea breeze (Arakawa and Utsugi, 1937; Hatcher and Sawyer, 1947; Leoopoled, 1949). Substantial work has been carried out on the climatological and observational aspects of sea breeze circulation on western and eastern coast of India (Ramadoss, 1931; Ramanathan, 1937; Roy, 1941; Ramakrishnan and Jambunathan, 1958; Ramanathan and Subbaramayya, 1965; Narayanan, 1967; Dekate, 1968; Sivaramakrishnan and Rao, 1989; Prakash et al 1993; Kunhikrishnan et al 1993; Prakash 1993; Radhika, 1994; Sunil, 1997; Sumabai, 1997; Ramana, 2001). The prevailing wind, land-sea thermal contrast, frictional retardation, surface heating are the factors that influence the time of onset, intensity and nature of sea breeze circulation (Prakash et al 1992). The sea breeze is one of the best known and well studied boundary layer mesoscale phenomena. Despite the long history of study of the sea breeze, there still remain many unanswered questions about its microscale structure and dynamics, especially in regions of complex or sloping topography (Wilczak et al 1996).
2.2 Outline of the work

In this chapter, the diurnal and seasonal variation of the boundary layer parameters such as air temperature, soil temperature, wind direction and speed are presented. The features of the sea breeze such as onset and cessation time and associated turbulent behaviours are discussed in the next section. The day to day variation of turbulent parameters associated with land breeze and sea breeze is discussed there after. Surface boundary layer height variations is derived from the spectral method is described in the next section.

2.3 Scope of the study

In this study, an attempt is made to bring out the various boundary layer features over Cochin during the land breeze and sea breeze period. Cochin is the one of the big industrial cities of Kerala state so that the study of the boundary layer features such as characteristics of wind, temperature, surface fluxes, drag coefficient, etc. are very important. The onset and cessation time and duration of sea breeze and associated turbulent fluxes are examined closely because these parameters are very important in the diffusion of pollutants in the atmospheric boundary layer.

2.4 Data and methodology

2.4.1 Description of the tower site

Micrometeorological tower observatory is established for boundary layer studies, at Cochin, in the western peninsular India (9° 58'N latitude and 76° 17'E longitude). The terrain around the tower is complex in nature with laterite soil. The shoreline over Cochin is almost parallel to longitude as indicated in Fig.2.1, the location of micrometeorological tower observatory system marked by T (shoreline is inclined to longitude by about 20° with western side is Arabian Sea and eastern side is Indian land mass) and is about 8 km away from the tower site. Fig.2.2 shows the micrometeorological tower system with three levels of sensors. The tower observatory system was set up at Thrikkakara, near south Kalamassery, Cochin (in the main campus of Cochin University of Science and Technology) in November, 2001. The tower has a height of 20 m with sensors for temperature, wind speed and wind direction mounted at three levels: 5 m, 10 m and 20 m. Sunshine recorder and sensor
Fig. 2.1 Location map of Cochin (Tower location is marked by T).

Fig. 2.2 Micrometeorological Tower of 20 m height with three levels of sensors installed at Cochin University Campus for atmospheric boundary layer studies.
for net solar radiation were installed at 10 m level and automatic rain gauge at the ground. The data set was collected in a regular interval of 30 minutes to compute the surface fluxes and other boundary layer parameters and fast response (1 Hz) data was procured during selected periods at an interval of 1 second to understand the evolution of the surface boundary layer height by the Fast Fourier Transformation analysis. Calibration and quality check of the observations from the tower system were carried out thoroughly. After completing the quality check, data set from the memory module was transferred to the data archives for the further analysis. Wind and temperature were observed for studying diurnal variation of the boundary layer parameters and their derived parameters.

2.4.2 Computation procedure

The wind direction, wind speed and temperature at 10 m and 20 m levels observed at the micrometeorological tower were used for the analysis of sea breeze/land breeze and associated features. The non rainy days were selected for the study during winter, pre-monsoon, southwest monsoon and post-monsoon seasons. A few instantaneous observations individually analysed for selected days in each season to bring out the characteristic boundary layer features for the season. The days chosen are 12th January (winter), 15th April (pre-monsoon), 23rd July (southwest monsoon) and 27th November (post-monsoon). Similarly, the mean features for January, April, July and November representing winter, pre-monsoon, southwest monsoon and post-monsoon respectively were also made to understand the general characteristics in respective seasons. Further, to study the boundary layer features during sea breeze and land breeze, long continuous data series (180 data points) during land breeze (around 8 am) and during sea breeze (around 3 pm) were prepared. The prevailing surface wind over Cochin during the southwest monsoon season is northwesterly and that in the other season is northeasterly.

Sea Breeze Component (SBC) was obtained by using the equation (Narayanan, 1967) \[ SBC = U \sin(340 - ddd) \]. Where \( U \) is the wind speed and \( ddd \) is the wind direction in meteorological angle. Cochin station is oriented to the coastline by 160-340 azimuth. Thus SBC is positive for sea breeze and negative for land breeze.
The fluxes of momentum and sensible heat are calculated by profile method. It is an indirect method based on Monin-Obukhov similarity theory for estimating surface fluxes. The profiles of wind and temperature in the surface layer are defined in the forms (Dyer and Hicks 1970, Businger et al 1971):

\[
\Delta \bar{u} = \frac{u_1 - u_2}{k} \left( \ln \frac{z_1}{z_2} - \psi_m(\zeta_2) + \psi_m(\zeta_1) \right),
\]

\[
\Delta \bar{\theta} = \frac{\theta_1 - \theta_2}{k} \left( \ln \frac{z_1}{z_2} - \psi_h(\zeta_2) + \psi_h(\zeta_1) \right),
\]

where \( \Delta \bar{u} = u_1 - u_2 \) and \( \Delta \bar{\theta} = \theta_1 - \theta_2 \), the subscripts denotes the level at 10m and 20m respectively \( u_1 \) is the frictional velocity and \( \theta_1 \) is the temperature scale. \( \psi_m \) and \( \psi_h \) are the stability functions associated with wind and temperature respectively. \( \zeta = z/L \) where \( L \) is the Monin-Obukhov length and is given by \( L = \frac{Tu^2}{gk\theta} \) and \( R = 0.74 \), a ratio of eddy diffusivities in neutral limit and \( k \) is the von Karman constant and the value is 0.4.

The stability functions are given as follows (Paulsen 1970; Barker and Baxter 1975):

In unstable condition \( (\zeta < 0) \):

\[
\psi_m(\zeta) = \ln \left( \frac{1 + x}{2} \right)^2 \left( \frac{1 + x^2}{2} \right) - 2 \arctan \left( 1 - \frac{\pi}{2} \right),
\]

\[
\psi_h(\zeta) = 2 \ln \left( \frac{1 + y}{2} \right),
\]

where \( x = (1 - 15\zeta)^\frac{1}{2} \), and \( y = (1 - 15\zeta)^\frac{1}{2} \),

in stable condition \( (\zeta > 0) \):

\[
\psi_m(\zeta) = -4.7\zeta, \quad \text{and} \quad \psi_h(\zeta) = -4.7 \frac{R}{\zeta},
\]

the frictional velocity and temperature scale are computed iteratively.
The drag coefficient can be determined from the relation \( C_d = \left( \frac{u_*}{U} \right)^2 \).

where \( U \) is the wind at reference height.

The fluxes of momentum can be calculated using the equations

\[ \tau = \rho u_*^2 \]

And sensible heat flux is found by \( SHF = -\rho C_p u_* \theta_* \).

where \( C_p \) is the specific heat capacity at constant pressure and value is 1004 Jkg\(^{-1}\)K\(^{-1}\)

### 2.5 Diurnal variation of boundary layer parameters

#### 2.5.1 Air temperature

The atmospheric temperature is mainly governed by the incoming solar radiation, it mainly depends on latitude and time of the day. Furthermore, it is affected by the nature of the surface of the underlying surface, by the altitude and by the prevailing wind. Diurnal variation of air temperature at the three levels (5 m, 10 m and 20 m) for different months is examined on a seasonal basis. Fig.2.3 shows the diurnal variation of air temperature at the three levels for winter, pre-monsoon, southwest monsoon and post-monsoon seasons. The mean diurnal variation of temperature for the four seasons is presented using data chosen for non rainy days in the respective seasons. The maximum diurnal variation of air temperature is found during winter season with a range of 13°C. This can be due to relatively cloud free situation during the season causing high maximum temperature and low minimum temperature due to less sunshine duration during winter. The lowest minimum temperature recorded during the observation period is 20°C in the month of February and highest maximum temperature is found to be more than 35°C in the month of March and April. This is in agreement with the variation in insolation in the northern hemisphere, which receives more solar radiation during pre-monsoon and southwest monsoon seasons. In general the minimum temperature is found just before the
sunrise and maximum temperature in the day is found around 3 pm local time (IST). Oke, 1978 observed similar diurnal variation over land regimes.

Fig.2.3 Diurnal variation of air temperature during four different seasons

2.5.2 Soil temperature

Soil temperature shows well-marked diurnal variation in upper part of the earth’s surface. Temperature penetration to depth is mainly depends upon the nature and thermal conductivity of the soil. The maximum diurnal variation is found in the upper level of the soil. Fig.2.4 shows the diurnal variation of soil temperature during winter, pre-monsoon, southwest monsoon and post monsoon seasons for 5 cm, 10 cm, 20 cm and 40 cm. The diurnal variation of soil temperature at 5 cm depth is almost same as that of air temperature at 5 m. The diurnal variation is maximum at 5 cm and minimum at 40 cm because the thermal conductivity of soil is small (the soil type in the observation site is laterite). At 40 cm depth, diurnal and seasonal variations are comparatively small. The annual mean temperature is maximum at 5 cm depth and minimum is at 40 cm. The time delay for reaching the temperature from 5 cm to 10 cm is almost 30 minutes. Thus temperature change by external forcing affects mainly in the top layer. The maximum diurnal variation is found during the winter season as
in the case of air temperature and the least is found during southwest monsoon and post monsoon seasons.

Fig. 2.4 Diurnal variation of soil temperature in different seasons at four depths

2.5.3 Wind speed

Diurnal variation of wind over Cochin station at the three levels for the four seasons is presented in Fig. 2.5. The wind speed is very small near the ground. At 5 m and 10 m levels, wind is almost calm during night hours in all the seasons owing to surface friction. The wind speed increases with height and the variation agrees with the general pattern of wind in the surface boundary layer i.e., the logarithmic profile as described in Stull, 1997. Generally, wind is calm during night time and increases due to the modulation of the local circulation by the sea breeze caused by differential heating as the day progresses. The wind strength is highest at 20 m among the 3 levels. Maximum wind speed of about 4 ms$^{-1}$ is found at 20 m level on a few days of July, which is attributed by the strong Low Level Jet stream at 850 hPa associated with the active situation of southwest monsoon. In most of the cases, maximum wind speed is found around 16 hours. The winds not only determine the travel time of pollutants from the source region to a given receptor but also control the ground level concentration. The calm/weak winds deteriorate the air quality. Thus better dispersal of pollutants can be expected in pre-monsoon season and less during winter season.
2.5.4 Wind direction

Diurnal variation of the wind direction observed during winter, pre-monsoon, southwest monsoon and post monsoon seasons are given in Fig.2.6. The local circulation induced by differential heating of the coastal region viz sea breeze is seen in all the cases. The transition time of wind direction from land breeze (around 90 degree during night time and early morning hours) to sea breeze (around 270 degree) is changing from day to day and also from season to season. Earliest sea breeze onset is found during southwest monsoon season and the delayed one occurs during post-monsoon season. Generally wind direction turns clockwise with height due to decrease in surface friction with height. However, during the onset of sea breeze or just before the onset the turning of wind direction with height becomes counter clockwise (backing).
2.6 Sea breeze and associated features

2.6.1 Diurnal variation of averaged wind direction

The features of sea and land breeze circulations are discussed using air temperature, wind direction and wind speed observed at 10 m and 20 m levels. The analysis was carried out considering all non-rainy days in the representative months of the seasons. The average diurnal variation of the wind direction for all the seasons is presented in Fig. 2.7. Solid line indicates for 10 m level and solid-dotted line is for 20 m level. In the winter season, average sea breeze period during the season is from 1500 hours to 2000 hours. In general, the prevailing surface wind during the season is easterly and it becomes westerly by the afternoon due to sea breeze circulation. In pre-monsoon the duration of sea breeze is slightly larger than that in winter. In general, the transition time from land breeze to sea breeze is less for the averaged pre-monsoon season compared to that during winter season, due to less variation of onset time of individual cases. The strength of sea breeze during this season is slightly higher than that in the winter season. Intermittent cloud clusters formed on most of the days during the southwest monsoon season reduces the insolation and hence the air temperature. So, the time of onset of sea breeze and its intensity vary widely. In
this season, sea breeze lasts for a long period due to more sun shine duration. Even though the intensity is small, land breeze is formed during this period. In the post monsoon season, the duration of sea breeze is small due to less sun shine duration and intermittent cloud clusters formed in association with pressure system.

![Graphs showing wind direction and duration](image)

**Fig. 2.7** Graphs showing wind direction and duration in different seasons.

Among the sea breeze circulation patterns in different seasons, it is found that maximum strength is during pre-monsoon, followed by southwest monsoon. This is contributed by high differential heating in these seasons. The duration of sea breeze is highest in southwest monsoon season followed by pre-monsoon, due to high sunshine duration in these seasons. The strength of land breeze is relatively small during southwest monsoon season compared to other seasons due to the prevailing surface westerly zonal wind in the southwest monsoon season. By further analysis of the averaged features, it is found that the time of onset and cessation of sea breeze on individual days during the same season vary widely. So, the averaged features may not reflect on seasonal sea breeze circulation properly. This can result in lengthy transition time of onset of sea breeze, absence of sea breeze characteristics such as decrease of temperature and wind speed at the time of onset, backing and veering
features in association with the sea breeze. Thus the sea breeze circulation is studied further by considering the temperature and wind on individual non-rainy days in different seasons to bring out the detailed sea breeze characteristics. The differential heating is small during overcast or rainy days and hence the land and sea breeze circulations are feeble. One case of a rainy day during southwest monsoon season was also presented.

The features for 12th January, representative of winter, 15th April for pre-monsoon, 23rd July for southwest monsoon and 27th November for post monsoon are given in Fig.2.8. Diurnal features of the wind direction and corresponding wind speed and air temperature associated with the sea breeze circulation are studied for the above representative days. In the case of winter, it is observed that sea breeze occurs from 1200 hours to 1900 hours. During this period the strength of wind is around 2 ms\(^{-1}\) at 20 m level. The transition from sea breeze to land breeze occurs from 1800 hours to 2100 hours. The mean wind direction of the land breeze on the day is around 76 degrees. The wind strength during this period is feeble at 20 m and is calm at 10 m. It is found that the wind direction turns anticlockwise with height (backs) just before/during the onset time of sea breeze. Air temperature decreases during the time of onset of sea breeze due to the cold air advection (Hsu, 1988). It is noticed that the wind speed decreases for a short period during the setting time of sea breeze due to the combined effect of land breeze and sea breeze in opposite directions. This behavior is evident when the transition from land breeze to sea breeze occurs rapidly. Similar features for 15th April, representing pre-monsoon, as in the case of winter, the strength of wind is more during the sea breeze and the wind is calm at 10 m level except during sea breeze. Since the transition from sea breeze to land breeze is slow, the decrease in temperature at the time of onset of sea breeze is not seen and backing is occurred just before the onset. On 23rd July representing southwest monsoon season, the duration of sea breeze circulation is highest in comparison with the other three seasons. This can be thought of attributed by the increase in insolation during summer. The sea breeze direction is between 270° and 280° and is steady whereas the land breeze direction is not steady (fluctuating about 90 degree) and the strength is feeble (less than 1 ms\(^{-1}\)). Similar features are noticed for 27th November (post monsoon). Decrease of temperature (though it is small) and wind speed are found due to rapid transition of land breeze to sea breeze. Another notable feature is almost same magnitude of land and sea breezes during this season. The prevailing wind
during the northeast monsoon season is easterly, which is relatively strong and modulates land breeze.

Fig. 2.8 Diurnal variation of air temperature, wind direction and wind speed for 12th January, representative of winter, 15th April for pre-monsoon, 23rd July for southwest monsoon and 27th November for post monsoon. Dotted solid line indicates 20 m level and solid line 10 m level.

Though we presented a few samples (one each for January, April, July and November considered here as representative for winter, pre-monsoon, southwest monsoon and post monsoon seasons), analysis was carried out with many cases in all the seasons. It is found that the turning of wind direction with height is clockwise with height (veering by the effect of surface friction) except just before/during the transition from land breeze to sea breeze. Accordingly, there is a sudden decrease of temperature for a very short period at the time of onset of sea breeze accomplished by
the backing (associated with cold air advection). The wind speed decreases at the time of onset of sea breeze, if the transition is rapid. So, the wind observed may be interpreted as the combined effect of the land/sea breeze and the prevailing synoptic wind. The prevailing wind direction is modified by the presence of local mesoscale circulation due to differential heating. The sea and land breezes are predominant compared to the synoptic wind and hence local features determine the resultant wind direction.

It is found that the wind direction turns clockwise with height during the periods other than just before or during the onset of sea breeze contributed by surface friction. The evolution of sea breeze from the land breeze is a slow process and full establishment of sea breeze takes place from 15 minutes to half an hour (confirmed with observations taken at 5 minutes interval). The sea and land breeze circulations are more sensitive at 20 m compared to that 10 m, indicating the frictional dissipation of the circulation.

2.6.2 Diurnal variation of sea breeze component

Fig.2.9 Diurnal variation of sea breeze component for representative days of the seasons
To understand the setting time of sea breeze and land breeze, the sea and land breeze components were obtained by using the above formula. The negative side of the graph represents the land breeze and the positive side indicates the sea breeze component. Fig.2.9 explains the sea and land breeze circulations, clearly indicating the onset and cessation time as well as the intensity of the sea breeze circulation for all seasons.

2.6.3 Diurnal variation during a rainy day

The land and sea breeze circulation during a rainy day is shown in Fig.2.10 (for 24th June). Since it was a rainy day, the land-sea temperature contrast is small and hence the local circulation induced by the differential heating is not occurred on this day. However, the wind direction is around 260 degree in both levels for the entire day. The prevailing synoptic wind over this region during southwest monsoon season is westerly and it is strong since the monsoon is active. So, the wind direction

![Graph showing diurnal variation](image)

Fig.2.10. Diurnal variation of air temperature, wind direction and wind speed during a rainy day (24th June).

happened to be westerly, though there is no sea breeze or land breeze. The wind speed is relatively high during the entire period due to the influence of low level jet, which is strong in the active monsoon situation. It is seen that the wind direction turns clockwise with height throughout the day due to the effect of surface friction.
Since no transition and no backing of wind. Similar features are seen during all rainy days in the southwest monsoon season.

### 2.6.4 Diurnal variation of turbulent fluxes

#### 2.6.4.1 Momentum flux

To understand the general dynamics of surface boundary layer during different seasons, diurnal variation of surface momentum flux during all non-rainy days together for the representative months of the seasons were studied. The averaged diurnal variation of momentum flux during winter, pre-monsoon, southwest monsoon and post monsoon seasons are given in Fig.2.11. The high values of momentum flux are found during pre-monsoon season attributed by high wind shear. The momentum flux values are found to be very high during the presence of sea breeze circulation, since the prevailing westerly surface wind as well as wind fluctuation is further modulated by the local heating during the afternoon hours of southwest monsoon season. In all these seasons, the mean surface momentum flux values are directed downward. Small momentum flux values are found during the presence of land breeze of southwest monsoon season, since the wind during this period is feeble.

![Fig.2.11. Diurnal variation of averaged momentum flux during the four seasons.](image-url)
2.6.4.2 Sensible heat flux

Diurnal variation of averaged sensible heat flux during the above four seasons estimated by the wind and temperature data during the non-rainy days together for the respective month is given in Fig.2.12. As in the earlier case, the mean sensible heat flux values are high during the afternoon of pre-monsoon season and low values are found to be in the winter season. It may be noted that the averaged pattern of sensible heat flux is directed upward during the entire period. The occurrence of surface based inversion layer is rare over this near equatorial coastal station and hence the averaged sensible heat flux is directed upward even during early morning of winter. It is found that average sensible heat flux during night time is almost zero in the winter and southwest monsoon seasons and during day time it is less than 150 Wm\(^{-2}\) in the winter season and more than 200 Wm\(^{-2}\) in the southwest monsoon season.

![Fig.2.12. Diurnal variation of averaged sensible heat flux during the four seasons.](image)

The averaged surface fluxes need not represent the actual situation due to smoothening of irregularities by the difference in time of onset of sea breeze etc. For a better understanding, the diurnal variation of surface momentum and sensible heat fluxes were studied by considering representative days in each season.
2.6.4.3 Momentum and Sensible heat fluxes for individual days

Diurnal variation of surface momentum flux for individual representative days for each season is presented in Fig.2.13. The range of values is slightly higher for individual case compared to mean for the season. During the southwest monsoon season, high values of momentum flux are seen during the presence of sea breeze. The intensity of momentum flux decreases during onset and cessation of sea breeze for all the cases. This is due to decrease of wind during the transition time as explained earlier. The momentum flux depends mainly on vertical wind shear and increases during after noon due to the influence of sea breeze. Fig.2.14 represents the diurnal variation of sensible heat flux for individual cases for different seasons. As expected, the sensible heat flux values are high during day time and small during night. Averaged surface momentum and sensible flux patterns resemble closely to the instantaneous pattern for all the seasons. Since the irregularities are smoothened in the average pattern, the range in the diurnal variation is less than that in the instantaneous for all the seasons. The land breeze over this station during the pre-monsoon season is prominent after 1900 hours, but this is not strong enough to record at 10 m level. So, the vertical wind shear is very high, causing the unusual behaviour of surface momentum flux for the representative case for pre-monsoon season. The sensible heat flux also decreases during the onset of sea breeze, similar to that of momentum flux. The cold air advection associated with the sea breeze results in the decrease of sensible heat flux at the time of onset of sea breeze. Among the four representative days considered here, sensible heat flux is found to be maximum during non rainy day in the southwest monsoon season, the maximum value is found to be 250 Wm$^{-2}$ around 1600 hours, followed by pre-monsoon season. This is attributed by the variation of insolation over this station, which is maximum during clear sky days of monsoon season, followed by pre-monsoon season. It may be noted that there is a situation of downward sensible heat flux during winter season due to the temperature inversion, though the winter effect is feeble over this near equatorial coastal station.
Fig.2.13. Diurnal variation of momentum flux during individual day of the seasons.

Fig.2.14. Diurnal variation of sensible heat flux during individual day of the seasons.

Variation of drag coefficient with wind speed during sea breeze and land breeze for the four seasons (representative days as in the earlier case) was presented in Fig.2.15 and Fig.2.16 respectively. Generally, sea breeze (westerly) is stronger than land breeze (easterly) in all the seasons. Accordingly, the drag coefficient power
relationship with wind is different for sea breeze and land breeze situations. The respective equations are presented in the corresponding figures. These equations can be employed for obtaining drag coefficient on a seasonal basis for sea breeze and land breeze.

![Fig. 2.15 Variation of drag coefficient with wind during sea breeze period.](image)

![Fig. 2.16 Variation of drag coefficient with wind during land breeze period.](image)

In general the properties of the boundary layer parameters are different during sea breeze and land breeze periods. To investigate thoroughly, we made two data sets
one during the land breeze time (8 am IST) and another set during the sea breeze time (3 pm IST). The data set has a length of 180 days starting from 2nd November, 2001 to 30 April 2002. The continuous data set was subjected to quality check.

2.7 TURBULENT BOUNDARY LAYER FEATURES

2.7.1 During land breeze

In general, during land breeze period the intensity of the wind and temperature is less than that during the sea breeze period. Fig. 2.17a, 2.17b, 2.17c and 2.17d represent the wind at 20 m level, temperature at 20 m level, frictional velocity and temperature scale respectively. It is found that the wind speed is generally less and average speed is around 1 ms⁻¹. The wind speed frequently crosses 2 ms⁻¹. The strength of the land breeze is almost same in all days under consideration. Temperature at 20 m level is presented in Fig. 2.17b, temperature during morning hours is less due to the less insolation, but the temperature increases afterwards due to the intensity of the insolation. During the study period the temperature ranges from 20°C to 29.4°C. The temperature shows an oscillation like feature around 30 day other than fluctuation. The average temperature over this period is around 24°C. Derived parameter such as frictional velocity and temperature scale are given in Fig. 2.17c and Fig. 2.17d respectively. The concept of frictional velocity in the boundary layer flow is first introduced by Prandtl (1949). The important scaling parameters in the similarity theory are that of wind and temperature (Monin and Obukhov, 1954). The frictional velocity is always independent of height but depends on the nature of the ground, magnitude of the wind and turbulent state of the atmosphere. The daily variation of frictional velocity ($u_*$) is highly fluctuating during the land breeze period and the values ranges from 0.001 ms⁻¹ to 0.194 ms⁻¹. The frictional velocity depends upon the strength of the wind speed and hence momentum flux. The average frictional velocity during the period is 0.05 ms⁻¹. The day to day variation of temperature scale ($t_*$) is varied in a range -0.93 to -0.1. The $t_*$ depends mainly on the temperature compared to wind. The minimum value of $t_*$ is found during the winter period due to the effect of temperature.
Fig. 2.17 Day to day variation of (a) surface wind, (b) temperature, (c) frictional velocity and (d) temperature scale during land breeze period.

Fig. 2.18. Day to day variation of (a) Momentum Flux, (b) Sensible Heat Flux, (c) Stability Parameter and (d) Drag coefficient during land breeze period.

Fig. 2.18a to Fig. 2.18d represent daily variations of momentum flux, sensible heat flux, drag coefficient and stability parameter respectively during land breeze period. All these parameters are computed using profile method described in
methodology section. The surface momentum flux during early morning hours around 8 pm IST are given in Fig.2.18a. The momentum flux shows high variability from day to day due to the effect of wind. The maximum momentum flux values are nearly 0.2 Nm$^{-2}$ and at the time of high values of momentum flux the wind gradient between two levels (10 m and 20 m) are high. The sensible heat flux during the period of land breeze is presented in Fig.2.18b. Computation of sensible heat flux is essential for the energy budget estimation. A knowledge of the sensible heat flux is useful for description of the dynamics in the atmospheric boundary layer dynamics. During study period the high values of sensible heat flux are noticed during December month. The sensible flux also shows the variability as that of momentum flux. The maximum sensible heat flux values are varied from $-15$ Wm$^{-2}$ to 250 Wm$^{-2}$. Sensible heat flux depends mainly on wind and temperature. Wind is a main contributing factor compared to temperature for sensible heat flux and it can be clear from the figure 2.21. The average value of the sensible heat flux during the hours of land breeze (early morning hours) is 70 Wm$^{-2}$. Variation of drag coefficient is given in Fig.2.18c; the drag coefficient is highly varying from day to day with an average value 0.03 over the region during early morning hours. Fig.2.18d describes the stability parameter ($z/L$) during land breeze obtained by profile method using iterative solutions. The $z/L$ shows negative values throughout the period indicating unstable condition.

2.7.2 During sea breeze

All the described above are studied separately for the sea breeze case to differentiate the features of the surface boundary layer from land breeze. The Fig.2.19a, 2.19b, 2.19c and 2.19d are represented the wind at 20 m level, temperature at 20 m Level, frictional velocity and temperature scale respectively. In Fig.2.19a shows the daily variation of wind speed during the sea breeze time (3 pm IST). Sea breeze is fully established by this time. Generally wind speed increases with time in the day. From the figure, the wind speed is varying with an average value of 2.3 ms$^{-1}$. The wind speed in certain days exceeds 3.8 ms$^{-1}$. The strength of the sea breeze during this period is varied from month to month. The maximum wind is found during the pre-monsoon periods (April). Fig.2.19b shows the daily variation of air temperature during 3 pm. Here temperature varies from 26.6°C to 34.3°C and this variation is may due to the seasonal difference in insolation by the sun. The average temperature
is around 31°C. The maximum temperature is found during the month of April because April month receives more insolation due to relatively clear sky. The

![Graph showing daily variation of various parameters](image)

**Fig.2.19.** Day to day variation of (a) surface wind, (b) temperature, (c) frictional velocity and (d) temperature scale during sea breeze period.

![Graph showing daily variation of various parameters](image)

**Fig.2.20.** Day to day variation of (a) Momentum Flux, (b) Sensible Heat Flux, (c) Stability Parameter and (d) Drag Coefficient during sea breeze period.
derived parameter $u_{*}$ during sea breeze time is presented in Fig. 2.19c. The profile of the $u_{*}$ is almost same as that of the profile of the wind. The frictional velocity during sea breeze period varies from 0.03 ms$^{-1}$ to 0.6 ms$^{-1}$ and average value is 0.28 ms$^{-1}$. The variation of $u_{*}$ is varied from its average values $-0.45^\circ$C to a minimum of $-0.67^\circ$C and to the maximum of $-0.2^\circ$C (Fig. 2.19d).

Momentum flux, sensible heat flux, drag coefficient and stability parameter during the sea breeze is presented in Fig. 2.20a, 2.20b, 2.20c and 2.20d respectively. The profile of the momentum flux is very similar to the profile of the $u_{*}$ and hence to the wind. The average value of the momentum flux is 0.12 Nm$^{-2}$, the maximum value is found in the months of March/April. Sensible heat flux also shows its peak value during the period of March/April and it is due to the high insolation. The sensible heat flux shows its maximum in pre-monsoon season around 200 Wm$^{-2}$ and least is during winter season and the value is about 100 Wm$^{-2}$. The average sensible heat flux is 160 Wm$^{-2}$. Daily variation of drag coefficient is given in Fig. 2.20c, the drag coefficient shows some peaks during winter period and the value reaches about 0.9, the remaining periods the drag coefficient shows almost constant value. The average drag coefficient during the sea breeze period is $1.7 \times 10^{-2}$. Time series plot of stability parameter is given in Fig. 2.20. Here, also the value is negative throughout indicating unstable condition.

Generally the values of the boundary layer parameters during sea breeze period is more than that during the land breeze time. The modulation of the parameters during the sea breeze period is due to the land-sea thermal contrast and hence the development of the sea breeze. But the values of drag coefficient is high during the period of land breeze. It may due to the reduced wind speed in land breeze time.

2.7.3 Dependence of wind speed and temperature on boundary layer parameters

Since it is very difficult to obtain the boundary layer parameters directly, an attempt is made to obtain the relations involving the wind and temperature so that boundary layer parameters can be obtained for the given values of wind and temperature. Fig. 2.21a and 2.21b are variation of boundary layer parameters to the wind and to the temperature respectively. From the figure, it is clear that the $u_{*}$, momentum flux,
sensible heat flux are functions of wind, and these parameters are linearly related to wind speed. The drag coefficient decreases with the increase of wind speed up to a critical value and beyond which $C_d$ increases with wind speed. From the figure it is clear that the stability parameter has not any relation to the wind.

Fig. 2.21a. Dependence of boundary layer parameters with wind

Fig. 2.21b. Dependence of boundary layer parameters with temperature
speed but the relation with temperature is clearly seen and the functional fit is the polynomial equation. Temperature scale is more related to the temperature and least to the wind speed. The relation with temperature is treated as linear.

An automatic weather station (AWS) of 20 m height was installed over Cochin, a tropical coastal station to study the micrometeorological properties on a diurnal and seasonal basis. This data set has a good reliability and no other data sets are available in this region. In this perspective this study using this data has attained its importance. The main feature studied using the above data set was the characteristics of the sea breeze and land breeze circulations. The setting and cessation time of sea breeze is very important over the station because Cochin is an industrial capital of Kerala state. The setting time of sea breeze is early in the southwest monsoon months followed by the pre-monsoon, winter and post monsoon periods during the clear sky days. These variations are occurs due to the difference in insolation during different months. Due to the orientation of the shoreline the direction of land breeze is 90° (i.e easterly) and the direction for sea breeze is 270° (i.e westerly). The fluxes of momentum and sensible heat and other parameters such as drag coefficient, frictional velocity, temperature scale, Monin-Obukhov length are computed using the Monin-Obukhov similarity relation on diurnal and seasonal time scales. The momentum and sensible heat flux show high diurnal variation during pre-monsoon period and the values are 0.28 Nm\(^{-2}\) and 250 Wm\(^{-2}\) respectively. The least variation of the fluxes is noticed during post monsoon period and the values are 0.1 Nm\(^{-2}\) for momentum flux and that for sensible heat flux is 150 Wm\(^{-2}\). The day to day variation of the parameters such as frictional velocity, temperature scale, drag coefficient, Monin-Obukhov length are examined during land breeze (8 AM) and sea breeze (3 PM) periods and concluded that the turbulent parameters are less during land breeze period due to the less intensity of the land breeze time and high during sea breeze hours because of the high turbulence and convective activities.