

Boundary layer characteristics associated with sea breeze circulation over Cochin

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(Received 1 March 2005)

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सार – इस शोध-पत्र में वायु तापमान, पवन गति और दिशा संबंधी आँकड़ों के 300 से भी अधिक दैनिक प्रेक्षणों का उपयोग करते हुए कोचीन की समुद्री और स्थलीय हवाओं, सतही पलक्सों और कर्षण गुणांक के अभिलक्षणों का अध्ययन किया गया है। वर्षा अथवा मेघ के कारण समुद्री हवा के परिसंचरण की अवधि और तीव्रता बदलती रहती है क्योंकि यह विभेदी उष्मा को कम करती है। भूमध्यरेखीय केन्द्र के निकट शीत ऋतु की अपेक्षा ग्रीष्म ऋतु में समुद्री हवाएँ पहले चलने लगती हैं। सभी ऋतुओं में समुद्री हवाएँ लगभग समान रूप से थम जाती हैं और यह लगभग 1900 घंटों के लिए होती है। सभी ऋतुओं में समुद्री हवाएँ लगभग पश्चिमी दिशा की ओर बहती हैं तथा स्थलीय हवाएँ लगभग पूर्वी दिशा की ओर बहती हैं। अधिकांश स्थितियों में समुद्री हवा के चलने के समय, तापमान और पवन की गति के कम होने और स्थल से समुद्र की ओर चलने वाली हवाओं में परिवर्तन की अवधि के दौरान पवन की दिशा का उँचाई पर मुड़ कर वामावर्त होने का पता चला है। सभी ऋतुओं में संवेग पलक्स अधोमुखी होता है। मानसून – पूर्व ऋतु में समुद्री हवा के चलने के दौरान संवेग पलक्स के मान उच्च पाए गए हैं। पूरी अवधि में औसत संवेद्य उष्मा पलक्स उपरिमुखी होता है और यह शीत तथा मानसून ऋतुओं में रात्रि के समय लगभग शून्य होता है। अधिकांश घटनाओं में समुद्री हवा के चलने और इनके रुकने की अवधि में संवेग पलक्स की तीव्रता कम हो जाती है। समुद्री हवा के चलने के समय संवेद्य उष्मा पलक्स समुद्री हवा से मिलकर ठंडी हवा के अभिवहन के कारण कम हो जाते हैं। सभी ऋतुओं में सतही संवेग और संवेद्य पलक्स पैटर्न औसतन काफी हद तक तात्कालिक पैटर्न के समान होते हैं। सामान्यतः स्थलीय हवा की अपेक्षा समुद्री हवा सभी ऋतुओं में अधिक प्रबल होती है। इसलिए समुद्री हवा और स्थलीय हवा परिसंचरण, पवन के कर्षण गुणांक के संबंध प्रभावी रूप से भिन्न होते हैं।

ABSTRACT. Features of sea and land breezes, surface fluxes and drag coefficient over Cochin are studied using more than 300 daily observations of air temperature, wind speed and direction data. The duration and intensity of sea breeze circulation vary with the rain or cloud as it reduces the differential heating. Onset of sea breeze is early in summer season for the near equatorial station compared to winter season. Cessation is almost same for all seasons and is around 1900 hours. The sea breeze circulation is almost westerly and land breeze circulation is almost easterly in all the seasons. It is found that in most of the cases, the temperature and wind speed decreases at the time of onset of sea breeze and turning of wind direction with height becomes counter clockwise (backing) during the transition period from land breeze to sea breeze. In all seasons, the momentum flux is directed downward. High values of momentum flux were found during the presence of sea breeze in pre-monsoon season. Average sensible heat flux is directed upward during the entire period and during nighttime it is almost zero in the winter and monsoon seasons. The intensity of momentum flux decreases during onset and cessation of sea breeze for all the cases. 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. Averaged surface momentum and sensible flux patterns resemble closely to the instantaneous pattern for all the seasons. Generally, sea breeze is stronger than land breeze in all the seasons. Accordingly, the drag coefficient power relationship with wind is different for sea breeze and land breeze circulations.

Key words – Sea breeze circulation, Monsoon boundary layer, Surface fluxes, Drag coefficient, Diurnal variation.

1. Introduction

Sea breeze circulation is 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. 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

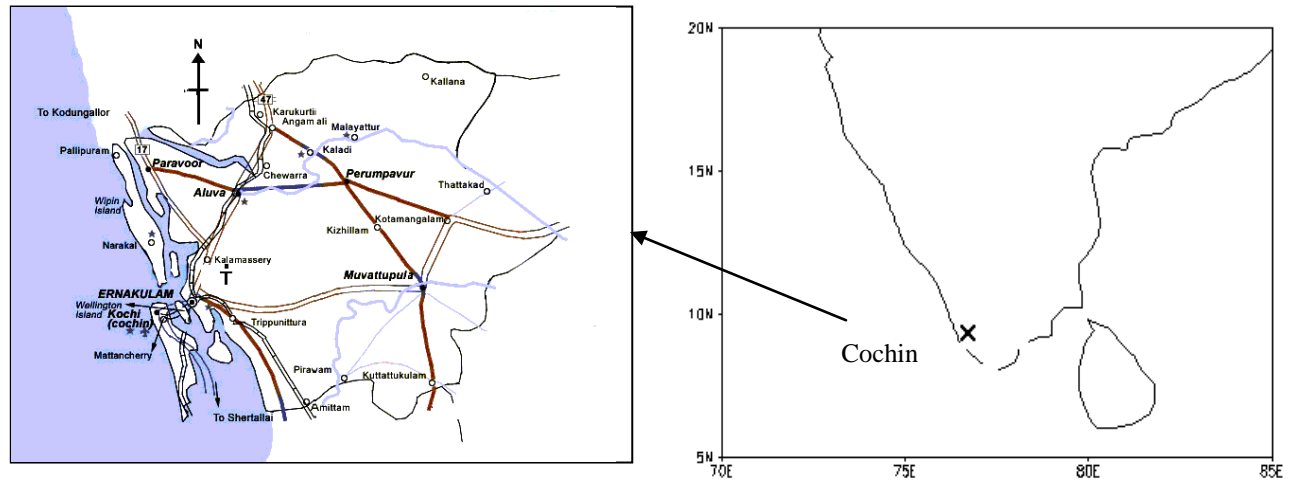


Fig. 1. Location map of Cochin station and tower site

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 setting time, maximum intensity, cessation period, 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). Nakane and Sasano (1986) used high-resolution measurements with the help of a Lidar to study sea breeze events. 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. Other observational studies on horizontal structure of sea breeze circulation carried out by Wakimoto and Atkins (1994) and Atkins and Wakimoto (1997) found that the gradients 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 afternoon 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. Yoshikado (1990) used soundings for the observational studies on sea breeze. Kitada (1987) studied to predict the dynamical behaviour of eddy diffusivity, turbulent kinetic energy and its dissipation rate associated with moving sea breeze front.

Many attempts were made to study the surface fluxes and transfer coefficient over the mid latitude region (Smith and Banke, 1975; Sethuraman and Reynor, 1975; Large and Pond, 1981). Monsoon Boundary Layer Experiment (MONTBLEX - 1990) conducted over the monsoon trough region of the Gangetic plain (Sivaramakrishnan *et al.*, 1992; Kusuma *et al.*, 1991, 1995; Kusuma and Narasimha, 1996) and Land Surface Process Experiment (LASPEX-1997) conducted over Sabarmaty basin brought out boundary layer characteristics over the tropical region. A few studies were made to understand the boundary layer characteristics near equatorial coastal station. Ramachandran *et al.* (1994) studied the surface roughness and turbulent intensity over Trivandrum. Here, an attempt is made to understand further on boundary layer characteristics over another coastal station, Cochin during different seasons.

The objective is to bring out the characteristics of sea and land breeze circulation and to study the surface

momentum and sensible heat fluxes and drag coefficient associated with sea and land breeze circulation over a near equatorial station, Cochin. The station is located in the southern region over the west peninsular India, where the monsoon has a prominent role. To understand the features, the diurnal variation of flux values associated with sea and land breeze circulation during the four different seasons are studied. A knowledge of the boundary layer characteristics associated with sea breeze and land breeze is very much useful in the local climate and modelling studies.

2. Data and methodology

The data used for the study is from a 20 m micrometeorological tower observatory 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. 1, with 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 land) and is about 8 km away from the tower site. The wind direction, wind speed and temperature at 10m and 20m levels observed at the micrometeorological tower were used for the analysis. The observations on many non-rainy days during winter, pre-monsoon, southwest monsoon and post-monsoon seasons were considered for the study. 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, considering the non-rainy days in these months to understand the general characteristics in different seasons. 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):

$$\Delta \bar{u} = \frac{u_*}{k} \left(\ln \frac{z_1}{z_2} - \psi_m(\zeta_2) + \psi_m(\zeta_1) \right),$$

$$\Delta \bar{\theta} = R \frac{\theta_*}{k} \left(\ln \frac{z_1}{z_2} - \psi_h(\zeta_2) + \psi_h(\zeta_1) \right),$$

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_* is the frictional velocity and θ_* is the temperature scale. ψ_m and ψ_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 $L = \frac{\bar{T} u_*^2}{gk\theta_*}$ 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 ($\zeta > 0$):

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

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

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

in stable condition ($\zeta < 0$):

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

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.

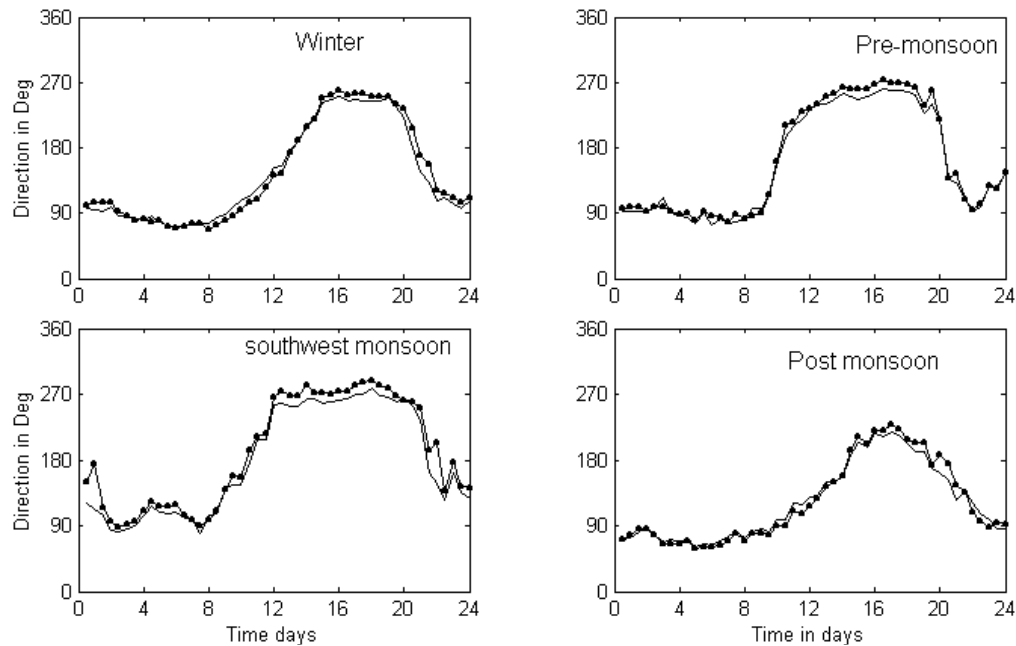


Fig. 2. Average diurnal variation of wind direction for winter, pre-monsoon, southwest monsoon and post monsoon seasons. Dotted – solid line indicates 20m level and solid line is for 10m level

3. Results and discussions

The features of sea and land breeze circulations are discussed using air temperature, wind direction and wind speed observed at 10m 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. 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, since it 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 formed during this period. The duration of sea breeze is small due to less sun shine duration and intermittent cloud clusters formed in

association with pressure system in the post-monsoon season.

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 attributed by high differential heating. The duration of sea breeze is highest during southwest monsoon 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.

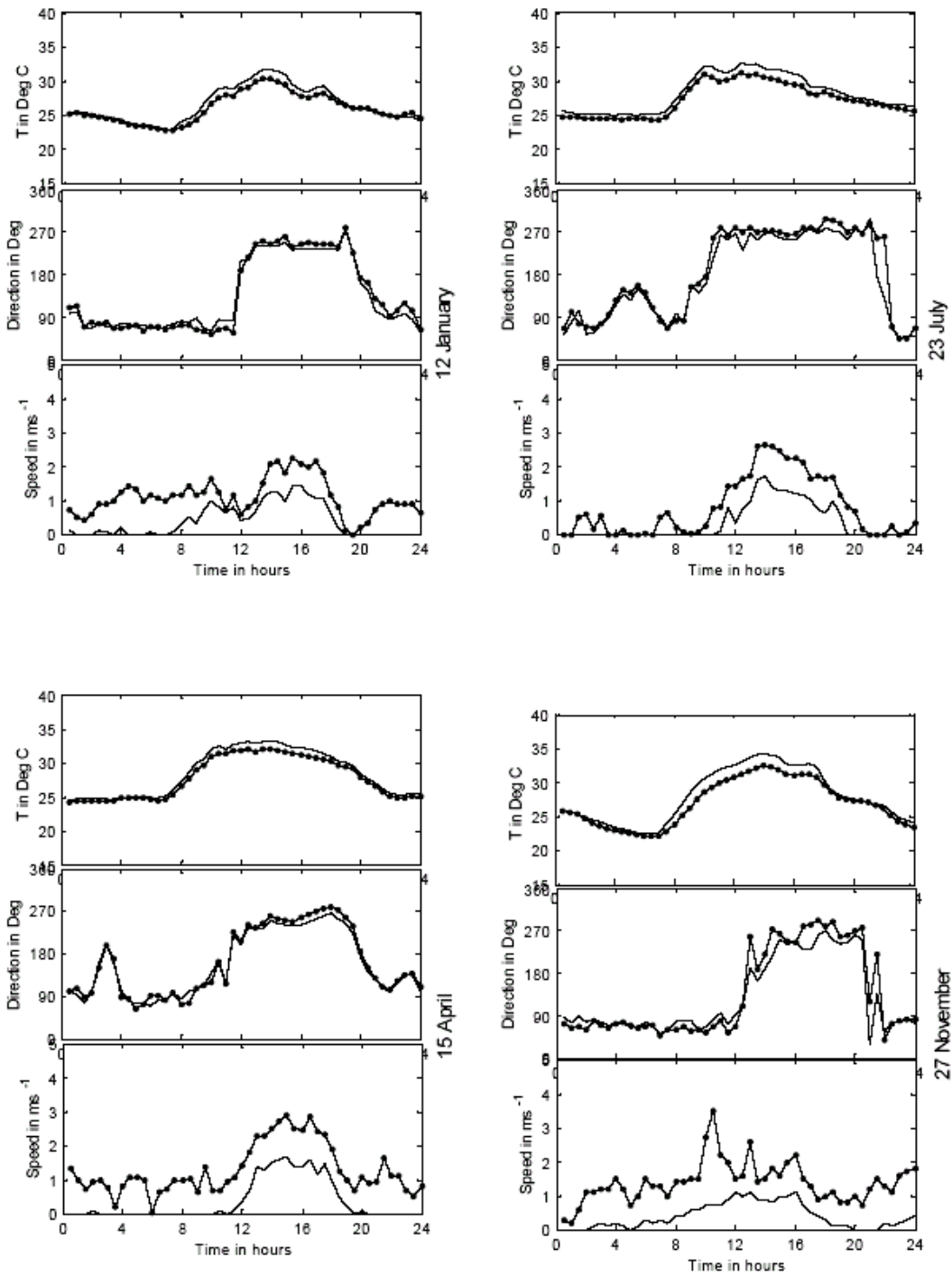


Fig. 3. Diurnal variation of air temperature, wind direction and wind speed for 12 January representing winter season, 15 April representing pre-monsoon, 23 July representing southwest monsoon season and 27 November representing post monsoon season

Fig. 3 represents the features for 12th January, representative of winter, 15th April for pre-monsoon, 23rd July for southwest monsoon and 27th November for post monsoon. Individual features of the wind direction and

corresponding wind speed and air temperature are plotted to get the features of wind speed and temperature associated with onset and cessation of sea breeze. In the case of winter, it is observed that sea breeze occurs from

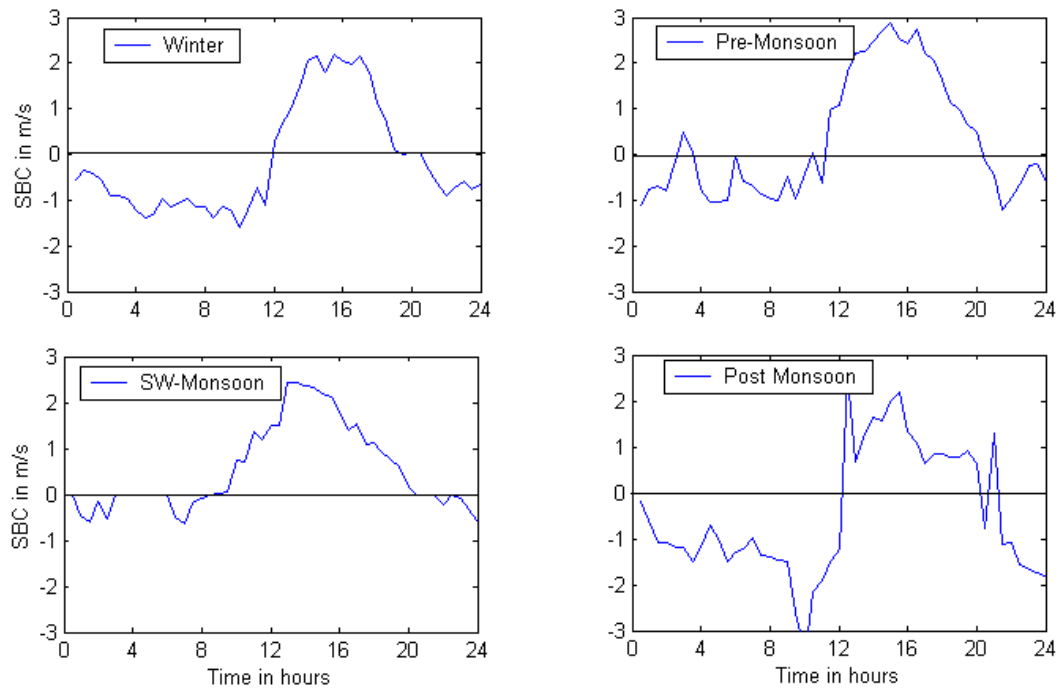


Fig. 4. Sea breeze component for instantaneous observation for different seasons

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 20m level and is calm at 10m level. It is found that the wind direction turns anticlockwise with height (backs) just before or during the onset of sea breeze. Accordingly, the air temperature decreases at the onset of sea breeze due to 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. 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) and decrease of temperature (though it is small) and wind speed is found due to rapid transition of land breeze to sea breeze. Another notable feature is almost same magnitude of land and sea breezes. The prevailing wind during the northeast monsoon season is easterly, which is relatively strong and modulates land breeze.

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. Since the sea and land breezes are predominant compared to the synoptic wind. Hence local features determine the resultant wind direction.

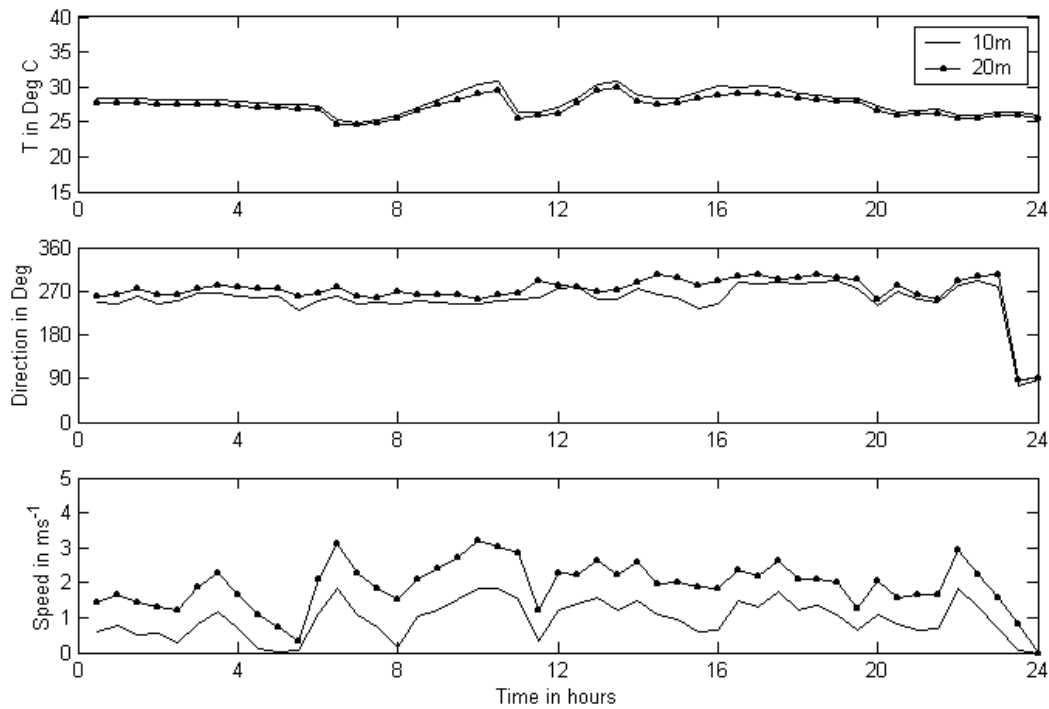


Fig. 5. Diurnal variation of air temperature, wind direction and wind speed for a rainy day in southwest monsoon season

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.

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. 4 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.

The land and sea breeze circulation during a rainy day is presented in Fig. 5 (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 west coast station during southwest monsoon season is westerly and

it is strong since the monsoon is active. So, the wind direction happened to be westerly, though there is no sea breeze. The wind speed is relatively high almost during the entire day because the low level jet stream is strengthened due to 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 on all rainy cases. Over the east coast stations, the direction of sea and land breeze is almost opposite to that over the west coast stations due to the difference in orientation of coastline.

To understand the general behaviour of surface boundary layer dynamics in different seasons, diurnal variation of mean surface momentum flux during non-rainy days together for the respective months were studied. Fig. 6 represents the diurnal variation of momentum flux during winter, pre-monsoon, southwest monsoon and post-monsoon seasons. 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

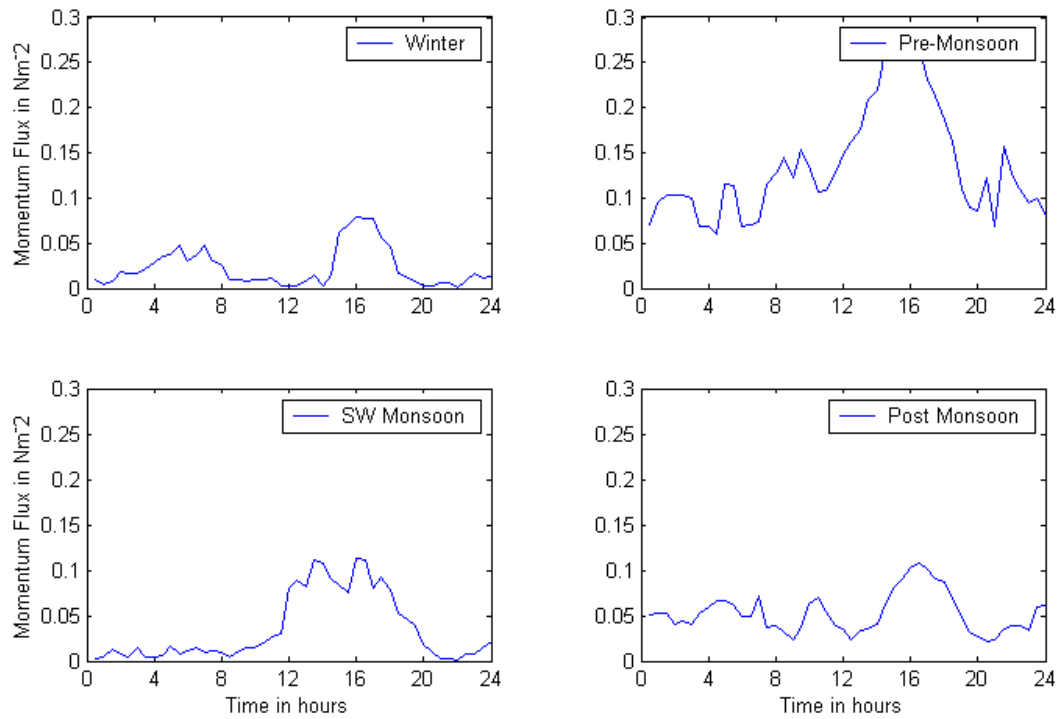


Fig. 6. Mean diurnal variation of momentum flux during different seasons

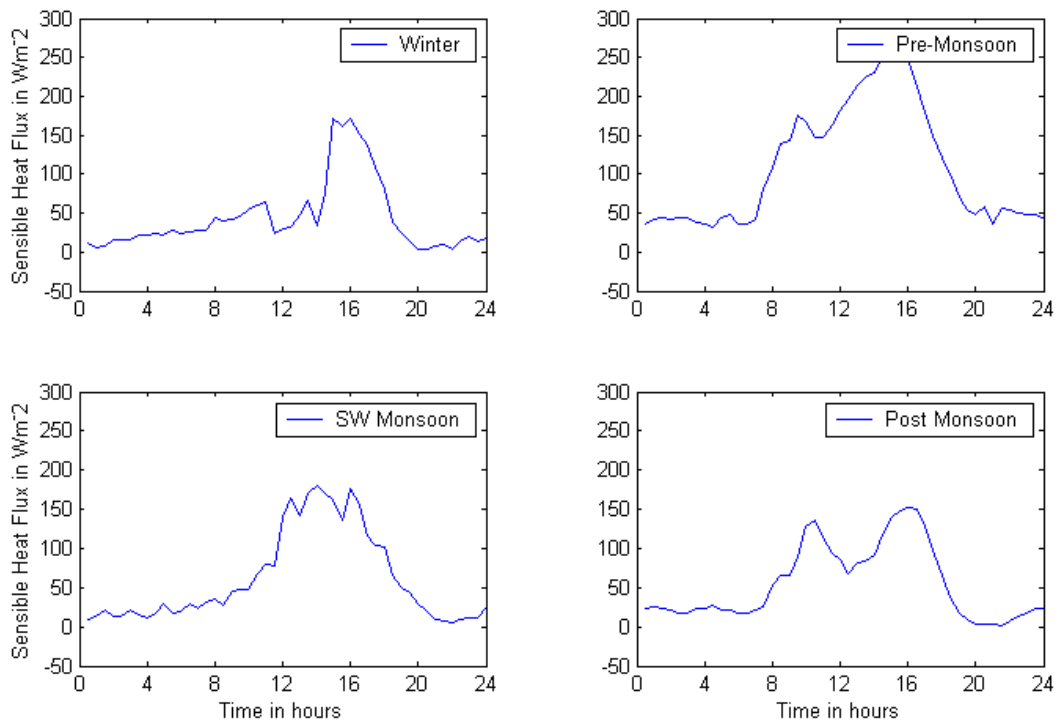


Fig. 7. Mean diurnal variation of averaged sensible heat flux during different seasons

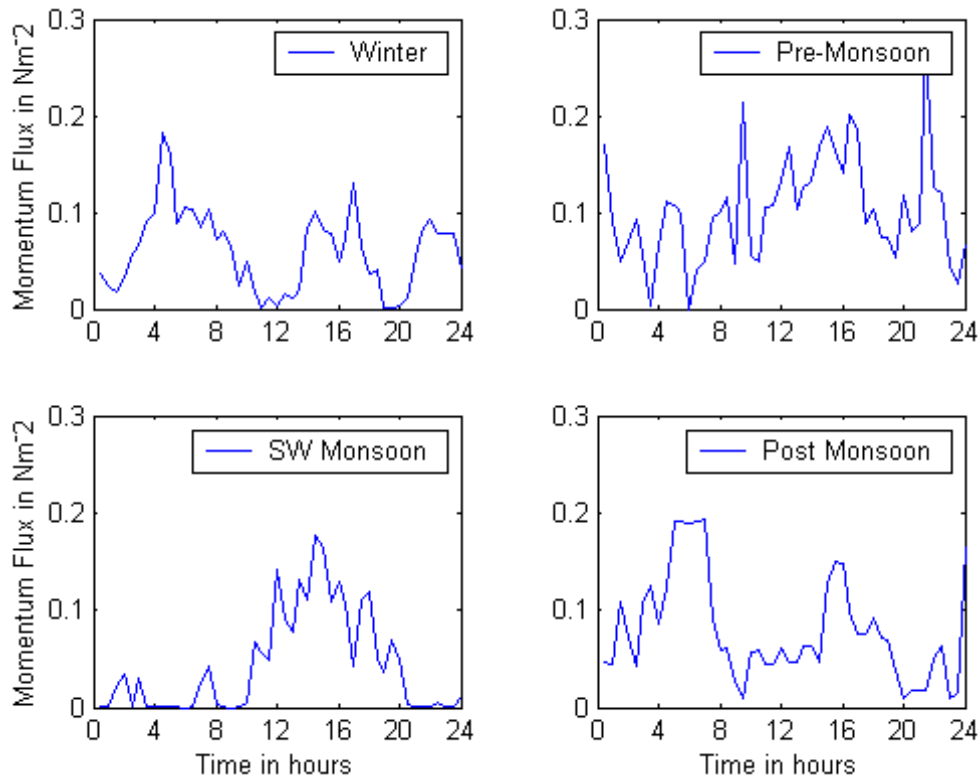


Fig. 8. Mean diurnal variation of surface momentum flux during different seasons

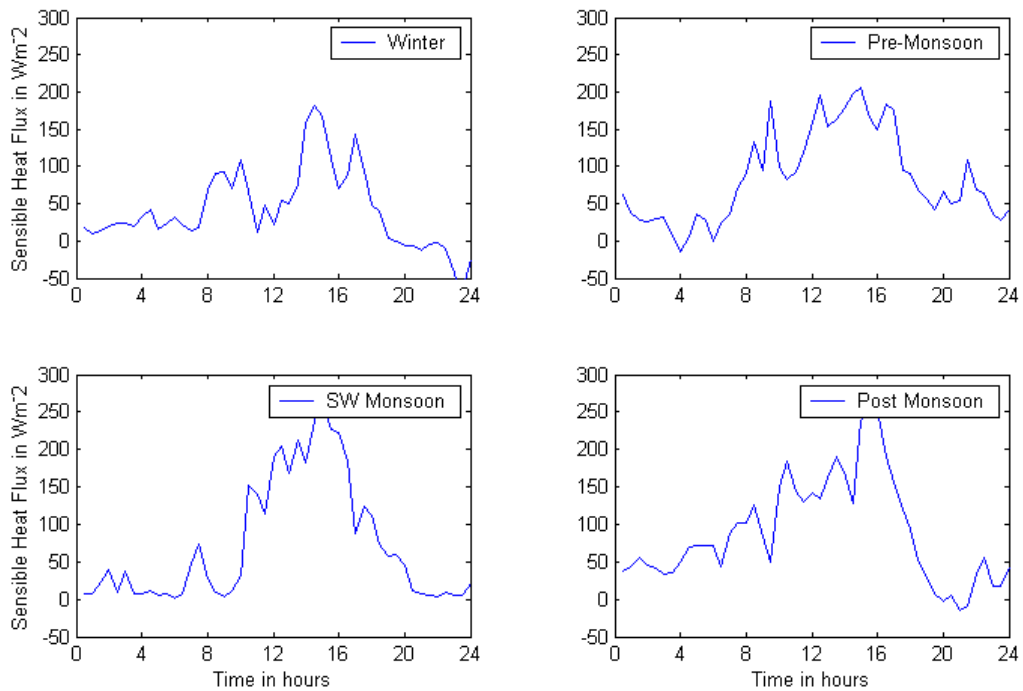


Fig. 9. Mean diurnal variation of sensible heat flux during different seasons

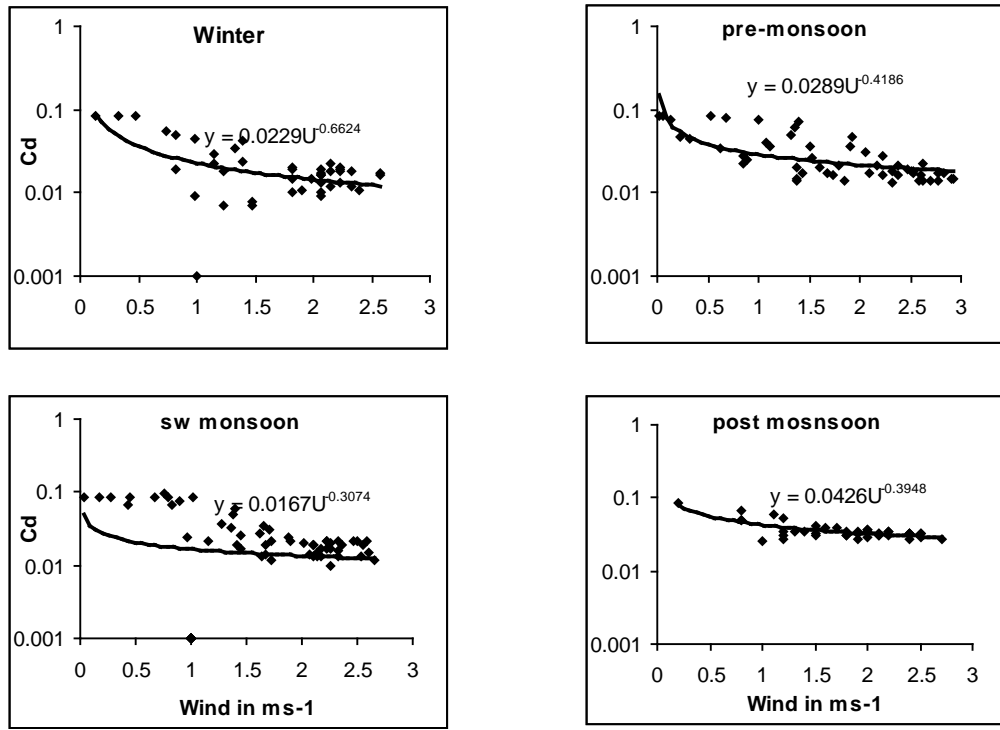


Fig. 10. Drag coefficient for sea breeze during different seasons

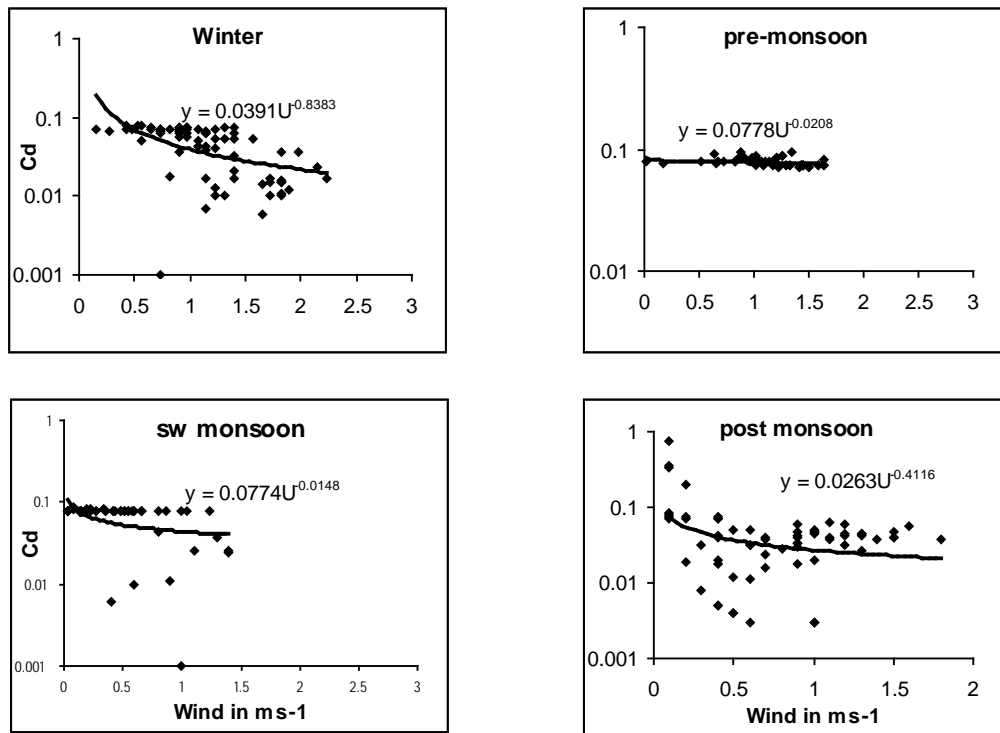


Fig. 11. Drag coefficient for land breeze during different seasons

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 very feeble.

Fig. 7 represents the diurnal variation of averaged sensible heat flux during the above four seasons estimated by considering the wind and temperature data during the non-rainy days together for the respective month. As in the earlier case, the mean momentum 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 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. 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.

Diurnal variation of surface momentum flux for individual representative days for each season is presented in Fig. 8. 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 is 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 presented earlier. The momentum flux depends mainly on vertical wind shear and increases during afternoon due to the influence of sea breeze.

Fig. 9 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 10m 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 maximum during clear sky 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.

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. 10 and Fig. 11 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 figures. These equations can be employed for obtaining drag coefficient on a seasonal basis for sea breeze or land breeze.

4. Conclusions

Onset of sea breeze over Cochin is early in southwest monsoon season compared to other seasons. Cessation is almost same for all seasons and is around 1900 hours. The sea breeze circulation is almost westerly and land breeze circulation is almost easterly during the entire period. Being a west coast station, the prevailing surface wind during monsoon season is westerly. Due to this reason, although differential heating is small during active monsoon situation, strong westerly is observed similar to the sea breeze. Over the west coast stations, the direction of sea and land breezes are almost opposite to that over the west coast stations. It is found that in most of the cases, at the time of onset of sea breeze temperature and wind speed decreases and wind backs. The momentum flux is directed downward and average sensible heat flux is directed upward in all the seasons. High values of momentum flux are found during the presence of sea breeze in pre-monsoon season. Average sensible heat flux during night time is almost zero in the winter and southwest monsoon seasons. The intensity of momentum flux decreases during onset and cessation of sea breeze for all the cases. Averaged surface momentum and sensible flux patterns resemble closely to the instantaneous pattern for all the seasons. Generally, sea

breeze is stronger than land breeze. Accordingly, the drag coefficient power relationship with wind is different for sea breeze and land breeze circulations.

Reference

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