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Characteristics of surface boundary layer during active and weak phases of southwest monsoon over Kochi: A tropical station

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ABSTRACT

This study explores the features of atmospheric surface layer over Kochi during active and weak phases of the southwest monsoon season. The classification of active and weak phases of monsoon is made on the basis of monsoon organized convection over the region. When the monsoon organized convection is over (away from) Kochi, considered it as an active (weak) phase. The study primarily utilizes sonic anemometer data. The diurnal variation of surface fluxes and turbulent kinetic energy (TKE) during active and weak conditions are examined in addition to surface wind and temperatures. It is found that monsoon clouds spread extensively over large area stabilizes the surface layer and a drastic decrease in sensible heat flux is observed during the active monsoon conditions. The average value of momentum flux and TKE decreases, surface layer becomes stable, and Atmospheric Boundary Layer (ABL) height lowers during active monsoon phase. A significant oscillation of 3.5 h periodicity is found to be embedded in the momentum flux and in the wind speed which is attributed to the penetration of the low level monsoon circulation. Weak monsoon phase is characterized by higher value of fluxes and TKE with higher amplitude of diurnal variation due to local heating and sea breeze circulation. Unstable condition between 00:00 IST and 01:00 IST and stable conditions in the early morning is observed during both active and weak phases. It is observed that there are two different relations for the growth and dissipation of fluxes and TKE. The dissipation is faster than growth in the case of surface fluxes with temperature. The sensible heat flux, momentum flux and TKE are logarithmically related with wind speed. Sensible heat flux has logarithmic relation with temperature, whereas momentum flux and TKE have exponential relation.

1. Introduction

Atmospheric Boundary Layer (ABL) is the lowest layer close to the Earth's surface where exchange of heat, momentum and water vapour takes place between the Earth's surface and the atmosphere. Surface layer (SL) is the lowest layer in the ABL, and has a height of about 10% of the ABL (Stull, 1988). Since the variation of surface fluxes are less than 10%, the layer is also called constant flux layer. The surface layer acts as the main link between surface forcing and the atmosphere above. Turbulence is the main factor responsible for the transport of heat, momentum, moisture and pollutants both horizontally and vertically in the surface layer (Sorbjan, 1989; Kaimal and Finnigan, 1994; Garratt, 1992). High resolution models used for the simulation of atmospheric parameters require proper boundary layer parameterisation, which needs better understanding of the boundary layer. Understanding the ABL features is also important in the studies of dispersion of pollutants.

Earlier studies of ABL in India and adjacent oceanic region was carried out through MONEX-77 (Monsoon Experiment), MONEX-99 (Holt and Sethu Raman, 1987; Parasnis and Morwal, 1991; Parasnis, 1991; Kusuma et al., 1991), IIOE (International Indian Ocean Experiment), ISMEX-73 (Indo-Soviet Monsoon Experiment) and Monsoon-77 experiments (Young, 1987; Colon, 1964; Sikka and Mathur, 1965; Pant, 1978). Monsoon-88 was conducted over the south western Arabian Sea covering pre-onset, onset and post onset phases of summer monsoon in order to understand the air-sea interaction and surface fluxes (Sadhuram et al., 1989; RameshBabu et al., 1992). MONTBLEX-90 (Monsoon Trough Boundary Layer Experiment) was the first large-scale field experiment conducted over the Indian continents to study boundary layer characteristics during the southwest monsoon season with special reference to monsoon trough region (Goel and Srivastava, 1990; Sivaramakrishnan et al., 1992; Kusuma et al., 1991, 1995;

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Kusuma and Narasimha, 1996; Kailas and Goel, 1996; Parasnis et al., 1991). Later on several studies have been conducted over different parts of India such as Thumba, Gadanki, etc (Nair et al., 2011; Krishnan et al., 2003; Basha and Ratnam, 2009).

Many studies have brought out the variation of surface layer parameters according to various tropical weather systems. Raman and Varma (1991) examined the boundary layer over the Bay of Bengal and found that surface layer is unstable during break/weak monsoon conditions and becomes near neutral with the re-establishment of monsoon circulation. Parasnis and Morwal (1991) reported an increase in stability of mixing line as the activity of monsoon change from break to active. Parasnis (1991) studied convective mixing in the monsoon boundary layer and found that the mixing line model together with the saturation point approach is able to depict different convective mixing regimes in the monsoon boundary layer. Kusuma et al. (1991) studied thermodynamic structure and heights of the boundary layer over the monsoon trough region of the Indian southwest monsoon and they could find significant and consistent variation in boundary layer heights between the active and break phases. Sivaramakrishnan et al. (1996) studied the fluxes of momentum and heat over sea surface during the passage of a depression in the north Bay of Bengal and found that the variations of heat and water vapour fluxes are in phase and momentum transfer during depression is two to three times larger. A few modelling studies were also reported in addition to the observational studies to quantify the response of surface layer to the meteorological events (Chatterjee et al., 1996; Potty et al., 1996). Venugopal et al. (2005) could find a significant inverse relationship between TCC (Total Cloud Cover) and SHF (Sensible Heat Flux) during various intensive observation periods of the MONTBLEX. The current study aims to deal with the ABL characteristics of a tropical coastal station (in the windward side of peninsular India) and the influence of low level circulation and organised convection during active and weak monsoon periods.

Kochi is an emerging industrial city, which is located at the southern part of west coast of India. During active monsoon, the Low Level Jet (LLJ) passes through peninsular India and during break monsoon the LLJ passes through the southern tip of peninsular India (Joseph and Sijikumar, 2004). The differential heating between sea and land produces sea breeze-land breeze system in all seasons with different duration and intensity (Hamza and Babu, 2007a). Babu and Hamza (2007) studied the features of ABL over Kochi during active and break monsoon situations using conserved variable analysis. They reported that the convective boundary layer height increases during weak phase of monsoon. Here, the study focuses on the variations of surface boundary layer features such as surface wind, temperature, momentum flux, sensible heat flux, TKE (Turbulent Kinetic Energy) and stability parameter (z/L) and ABL height during active and weak phases of the southwest monsoon over Kochi.

2. Data and methodology

Diurnal variation of surface boundary layer parameters during active and weak monsoon conditions have been studied using sonic anemometer data over Kochi (10°02′41″ N, 76°19′34″ E, 38 m above MSL). The instrument is situated at a height of 7 m above the ground level and provides three dimensional wind (u, v and w) and temperature (T) data in every 1 s interval. The three axis METEK sonic anemometer is capable of measuring wind velocity (u, v and w) in the range of ± 50 m s^{-1} with 0.1 m s^{-1} accuracy. The platinum wire thermometer measures temperature in the range of −30 to +50 °C with 0.01 °C accuracy. A brief description of the sonic anemometer established in the campus of Cochin University of Science and Technology, Kochi is explained in Jayakrishnan et al. (2013). Location map of the station is given in Fig. 1. MERRA (The Modern-Era Retrospective analysis for Research and Applications) hourly data (Bosilovich, 2008; Rienecker et al., 2011) with 0.625° X 0.5° horizontal resolution is used for the study of diurnal variation of ABL height. ECMWF (European Centre for Medium-Range Weather Forecasts) wind data (ERA-Interim; Dee et al., 2011) at 0.75° x 0.75° horizontal resolution is also utilized for giving the features of circulation during active and weak phases of the southwest monsoon season.

Most of the classifications of active and break monsoon are based on rainfall (Rajeevan et al., 2010), wind (Joseph and Sijikumar, 2004) and OLR (Outgoing Long wave Radiation, Krishnan et al., 2000) of central Indian region or monsoon core zone. Since Kochi is far away from the monsoon core zone, we define a new criterion based on the presence/absence of monsoon organised convection over Kochi to identify the active and weak monsoon situations of the region. The days are considered as active (weak) when the monsoon organised convection is over (away from) Kochi. The position of monsoon organised convection is identified based on the 0.25° X 0.25° daily averaged OLR data from Indian Institute of Tropical Meteorology (http://www.tropmet.res.in). If the value of OLR is less than (more than) 200 W m^{-2} over the region for a day, it indicates presence (absence) of monsoon organised convection. Using this criterion, we identified the active and weak days of the southwest monsoon season for the years 2008, 2009 and 2011 (three years) based on the availability of sonic anemometer data. The list of active and weak monsoon days utilised for the study is given in Table 1. In this study, we analyse the diurnal variation of micrometeorological parameters for the composite of 50 active and 105 weak monsoon days.

The surface layer parameters such as sensible heat flux, momentum flux, stability parameter and TKE are calculated using eddy correlation method as described by Arya (2001).

$$\text{Momentum flux,}\quad \tau = \rho u_*^2 \tag{1}$$

$$\text{Sensible heat flux,}\quad H = \rho C_p u_* \theta_* \tag{2}$$

Where,

$$\text{Friction velocity,}\quad u_* = \left(\left(\overline{u'w'}\right)^2 + \left(\overline{v'w'}\right)^2\right)^{1/4} \tag{3}$$

$$\text{Friction temperature,}\quad \theta_* = \frac{-\overline{w'T'}}{u_*} \tag{4}$$

$$\text{Stability parameter} = z/L \tag{5}$$

Where, z = 7 m (altitude of sonic anemometer from the ground) and

$$\textit{Obukhov length,}\quad L = \frac{\overline{T}\rho c_p u_*^3}{kgH} \tag{6}$$

$$\text{Turbulent Kinetic Energy,}\quad \text{TKE} = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{7}$$

Where ρ is the air density which is taken as 1.2 kg m^{-3}, C_p is the specific heat capacity of dry air at constant pressure (C_p = 1004 J K^{-1} kg^{-1}), k is the Von Karman constant (0.4), g is the acceleration due to gravity (9.8 m s^{-2}), u', v', w' and T′ are the fluctuations of wind components and temperature from the mean. For the computation of fluxes and statistical parameters the averaging time is taken as 10 min.

3. Results and discussions

3.1. Large scale features of active and weak monsoon conditions

Active (weak) phase of southwest monsoon is generally characterised by cloudy (clear) sky with continuous or intermittent rainfall (no rain or small amount of rainfall for very short duration less than an hour) situation. Fig. 2 indicates the OLR pattern over peninsular India during the active and weak phases of southwest monsoon (location of the study region is marked ‘x’ in the figure). The composite of OLR value over Kochi is less than 190 W m^{-2} during active phase and greater than 230 W m^{-2} during weak monsoon phase. During active phase, the organised convection is over the east Arabian Sea including the southwest coastal belt over the area 9°N-13°N, 72°E-77°E, where