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Response of surface boundary layer parameters during the formation of thunderstorms over Cochin

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ABSTRACT

In the present study we made a detailed analysis of the surface ABL parameters associated with three thunderstorms that occurred over Cochin during pre-monsoon season. The high-resolution sonic anemometer data can provide microscale evolution of the surface boundary layer processes. The parameters studied are momentum flux, sensible heat flux, Turbulent Kinetic Energy (TKE), friction velocity and variance of u, v, w, T. Momentum flux anomalously increases from 0.1 N m^{-2} to 1 N m^{-2} during the occurrence of thunderstorm. Correspondingly, sensible heat flux decreases anomalously to a value of -200 W m^{-2} from 10 W m^{-2}. TKE increases abruptly to 3 m^2 s^{-2} from 0.5 m^2 s^{-2} during convective activity. Friction velocity also changes abruptly to 1 m s^{-1} from 0.1 m s^{-1}. The thermodynamic parameters and stability indices were investigated prior to the occurrence of thunderstorms and found that the atmospheric characteristics were conducive for the formation of convective activity.

1. Introduction

The atmospheric scales of motion are generally classified into three major categories that are micro, meso and macro or synoptic scales. Of these, macro scale or synoptic scale has length scale greater than 1000 km and does not belong to the present scenario of thunderstorms. Meso scale has length from 10 to 100 km and microscale ranges between 1 and 10 km and comes into the scope of present study. A thunderstorm is considered here as a microscale or meso scale phenomenon, which has time scale of the order of less than an hour and length scale limited to 10 km. So a portion of the scale range spans the scope of micrometeorology (Arya, 2001; Asnani, 1995). The formation of a thunderstorm depends on the stability conditions and moisture that prevail in the atmosphere. An unstable atmosphere promotes upward motion as well as vertically developing clouds, which leads to the formation of cumulonimbus clouds and thunderstorms. The necessary elements that lead to the formation of thunderstorms are lift (orographic, frontal, or thermal), instability prevailing in the atmosphere and moisture in the lower troposphere. The lowest layer of the troposphere is called the Planetary Boundary Layer (PBL), in which the transfer of momentum, heat and moisture takes place between the surface layer and above (Stull, 1998). So it is necessary to have a better understanding of the mechanisms that lead to the thunderstorm formation in the surface boundary layer.

The behavior of an ultra sonic anemometer under cloudy conditions has been described in detail by Siebert and Teichmann (2000). Their study compares the behavior of sonic anemometer under cloudy and non cloudy days and confirms that there is no such dependency for clouds or rain on the performance of sonic anemometer. So the sonic anemometer data during cloudy and rainy days can also be used. The day time surface fluxes of radiation and heat at an inland station, Anand, is described by Nagar et al. (2002). They obtained a sensible heat flux value in the range 10–300 W m^{-2} directed upwards.

In association with the oceanographic and meteorological field experiments many results were reported on the atmospheric boundary layer in India as well as abroad. On a global basis, the tropical oceanic boundary layer has been analysed in connection with several field experiments that are: Atlantic Trade wind Experiment (Dunckel et al., 1974), Global Atmospheric Research Program Atlantic Tropical Experiment (GATE), Tropical Ocean and Global Atmosphere (TOGA), TOGA COARE. Over the Indian region the surface boundary layer has been extensively studied by several expeditions. A few of them are: LAnd Surface Processes EXperiment, conducted during January 1997–March 1999 over the Sabarmati basin of Gujarat state in western India; Bay of Bengal Monsoon Experiment (BOBMEX) (Bhat et al., 2001) carried out during July-August 1999 over the Bay of Bengal, TOGA COARE, aimed at elucidating the coupling of the West Pacific warm pool to

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the atmosphere (Webster and Lukas, 1992): MONSOON-77 and MONEX-79 . Apart from these two major cruise experiments, the Monsoon Trough Boundary Layer Experiment (MONTBLEX-90) was carried out over the northern plains of the Indian subcontinent during September-1999 (Goel and Srivastava, 1990).

The major studies conducted over the Indian region to analyse the surface layer parameters are discussed below. Raman and Varma (1991) computed the air-sea energy flux and stability of atmospheric boundary layer over the Bay of Bengal and found that the surface layers are unstable during break monsoon conditions and become near neutral with the re-establishment of monsoon circulation. Sanil Kumar et al. (1991) observed the mixed layer variability in east central Arabian Sea during pre-monsoon season of 1979 and utilized the results to model the mixed layer depth (MLD) following Niiler and Kraus (1977). 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 using cruise observation taken during MONTBLEX-90 and compared the variation prior to and after the period of depression. It was found that the variations of heat and water vapour fluxes are in phase and momentum transfer during depression is two to three times larger. Viswanadham and Satyanarayana (1996) analysed the atmospheric surface layer parameters during various epochs of monsoon over Varanasi using MONTBLEX-90. They analysed fluxes of momentum, sensible heat and latent heat flux as well as Turbulent Kinetic Energy. They could obtain the diurnal variation of TKE over Varanasi to be between 0.1 and 1 $m^2 s^{-2}$, sensible heat flux as −10 to 15 W m^{-2} and momentum flux to be 0.01–0.06 N m^{-2} at 15 m level. Pradhan et al. (1996) also studied the surface layer using MONTBLEX-90 data at Kharagpur. He could observe the diurnal variation of the momentum flux to be 0.1–0.4 N m^{-2} over the station. Murthy et al. (1996) studied the variability of the oceanic boundary layer characteristics in the northern Bay of Bengal during MONTBLEX-90 and the changes in the heat flux components were reported. Over the Indian region a few modeling 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). The work reported by Sen Guptha and Ramachandran (1998) gives an overview of the atmospheric boundary layer with special emphasis on tropical boundary layer. Jayakrishnan et al. (2013) analysed the variation of surface boundary layer parameters associated with the annular solar eclipse on 15th January 2010. They could report a sharp reduction in T.K.E and associated decrease in momentum flux, sensible heat flux and friction velocity during the annular solar eclipse. Sikka and Narasimha (1995) described in detail about the scope and motivation for carrying out the MONTBLEX experiment. Alappattu et al. (2008) studied the MABL characteristics during the ICARB campaign. They investigated the thermodynamic variables such as virtual potential temperature, specific humidity etc over the Arabian Sea and the Bay of Bengal.

In this study, we investigated the variation of surface boundary layer parameters associated with the convective activity during the formation of thunderstorms over a near equatorial coastal station, Cochin (located in the southwest peninsular India), during pre-monsoon season utilizing sonic anemometer and radiosonde data.

2. Data and methodology

We have made analysis on surface boundary layer parameters and thermodynamic parameters associated with the formation of three thunderstorms. The characteristics pertaining to the thunderstorm on 12th April, 2008 and the results on surface boundary layer parameters, thermodynamic parameters and stability indices associated with the thunderstorm are discussed in detail. The surface boundary layer parameters were computed based on sonic anemometer data as described in Arya (2001). Eddy correlation method was employed for the computation of the surface boundary layer parameters. The parameters computed are momentum flux, sensible heat flux, turbulent kinetic energy, friction velocity and variance of u, v, w and T. The sonic anemometer USA-1 (METEK, GmbH, Germany) was operational in Cochin University campus Thrikkakara (10°02′41″ N, 76°19′34″ E, 38 m above msl) since January, 2008. It provides zonal, meridional and vertical components of wind and air temperature at each second. With the availability of this fast response instrument installed at a height of 7 m above ground level we are able to get continuous observation of wind and temperature at the meteorological observatory. The data sets were archived and processed after a quality check.

The eddy correlation method is used to compute different parameters following formulae,

$$\text{Momentum Flux} = \rho u_*^2 \quad (1)$$

$$\text{Sensible Heat Flux} = -\rho C_p u_* \theta_* \quad (2)$$

where

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

$$\theta_* = \overline{w'\theta'}/u_* \quad (4)$$

$$\text{Turbulent kinetic energy (TKE)} = 1/2\ (u'^2 + v'^2 + w'^2) \quad (5)$$

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 as 1004 J K^{-1} kg^{-1}, v', w' and T' are the fluctuations of wind and temperature components from the mean, as described in Stull (1998). The averaging time adopted for computing the fluxes are 10 min.

The different variances are computed as

$$\text{Variance of } u = \overline{u'^2} \quad (6)$$

$$\text{Variance of } v = \overline{v'^2} \quad (7)$$

$$\text{Variance of } w = \overline{w'^2} \quad (8)$$

$$\text{Variance of } T = \overline{T'^2} \quad (9)$$

The thermodynamic parameters, CAPE (Convective Available Potential Energy), CINE (Convection Inhibition Energy) and different stability indices were evaluated from the radiosonde data (procured from the RAOB site: (http://www.esrl.noaa.gov/raobs/) as per the detailed methodology described in Babu (1996) based on the following equations

$$\text{CAPE} = -\int_{P_{LFC}}^{P_{LNB}} (T_{vp} - T_{ve}) R_d\, d(\ln P) \quad (10)$$

$$\text{CINE} = -\int_{P_{Surface}}^{P_{LFC}} (T_{vp} - T_{ve}) R_d\, d(\ln P) \quad (11)$$

where P_{LFC} is the level of free convection for the air parcel raised from the surface, P_{LNB} is the level of neutral buoyancy for the parcel, T_{ve} is the virtual temperature of the environment at pressure level P through which parcel rises, T_{vp} is the virtual temperature of the parcel and $_{Rd}$ is ideal gas constant for dry air.