Atmospheric Research 143 (2014) 198–215

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Evaluation of atmospheric turbulence, energy exchanges and structure of convective cores during the occurrence of mesoscale convective systems using MST radar facility at Gadanki

A.N.V. Satyanarayana [a,*], Sabiha Sultana [a], T. Narayana Rao [b], S. Satheesh Kumar [b]

[a] Centre for Oceans, Rivers, Atmosphere and Land Sciences, Indian Institute of Technology Kharagpur, Kharagpur 721 302, India
[b] Clouds and Convective Systems Group, National Atmospheric Research Laboratory, Gadanki 517 112, India

ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form 16 February 2014
Accepted 19 February 2014
Available online 26 February 2014

Keywords:
Planetary boundary layer
Mesoscale convective system
Turbulence transport
MST radar
Thunderstorm
Doppler Weather Radar

ABSTRACT

Mesoscale convective systems (MCSs) wreak lots of havoc and severe damage to life and property due to associated strong gusty winds, rainfall and hailstorms even though they last for an hour or so. Planetary boundary layer (PBL) plays an important role in the transportation of energy such as momentum, heat and moisture through turbulence into the upper layers of the atmosphere and acts as a feedback mechanism in the generation and sustenance of MCS. In the present study, three severe thunderstorms that occurred over mesosphere–stratosphere–troposphere (MST) radar facility at National Atmospheric Research Laboratory (NARL), Gadanki, India, have been considered to understand turbulence, energy exchanges and wind structure during the different epochs such as pre-, during and after the occurrence of these convective episodes. Significant changes in the turbulence structure are noticed in the upper layers of the atmosphere during the thunderstorm activity. Identified strong convective cores with varying magnitudes of intensity in terms of vertical velocity at different heights in the atmosphere discern the presence of shallow as well as deep convection during initial, mature and dissipative stages of the thunderstorm. Qualitative assessments of these convective cores are verified using available Doppler Weather Radar imageries in terms of reflectivity. The MST radar derived horizontal wind profiles are in good comparison with observed radiosonde winds. Significant variations in the surface meteorological parameters, sensible heat flux and turbulent kinetic energy as well as horizontal wind profiles are noticed during the different epochs of the convective activity. This work is useful in evaluating the performance of PBL schemes of mesoscale models in simulating MCS.

1. Introduction

The depth and the structure of the atmospheric boundary layer (ABL) are determined by the physical and thermal properties of the underlying surface in conjunction with the dynamics and thermodynamics of the lower atmosphere (Stull, 1988). Surface fluxes of heat, moisture, momentum, and vertical mixing in the ABL play important roles in the development and intensification of the thunderstorms (Anthes, 1982). Among all, ABL and convection have long been recognized as processes of central importance in the genesis and intensification of mesoscale convective systems (MCSs). Braun and Tao (2000) stated that ABL is a critical factor because of the generation of large fluxes of heat, moisture, and momentum in this thin layer. Through turbulent mechanism, eddies in the ABL transport the required moisture into the upper layers of the atmosphere for the sustenance of these events. MCSs are an important link

* Corresponding author. Tel.: +91 3222 281820/281821; fax: +91 3222 255303.
E-mail addresses: anvsatya@coral.iitkgp.ernet.in, achanta.satya@gmail.com (A.N.V. Satyanarayana).

http://dx.doi.org/10.1016/j.atmosres.2014.02.016
0169-8095/

between atmospheric convection and large scale atmospheric circulation (Houze, 2004). Mesoscale shallow convections are 1 to 2 km deep, and they have horizontal length scales of a few kilometers. Pucillo and Manzato (2013) have studied the skill of one or more predictors such as wind magnitude, equivalent potential temperature, and moisture transport in forecasting the highest radar for Vertical Maximum Intensity reflectivity which in turn assesses the signature of the storm occurrence and intensity. Csirmaz et al. (2013) investigated two cases of the thunderstorms with rotating characteristics that are formed in an environment of relatively low or moderate wind shear in the lowest 6 km layer of the troposphere. Mäkelä et al. (2014) have investigated pre-monsoon thunderstorm characteristics over Nepal.

Mesoscale shallow convection is worth studying given its role in the transportation of heat, moisture and momentum into the free atmosphere and also in improving our understanding of the dynamics of the ABL (Agee, 1987; Moyer and Young, 1994; Blaskovic et al., 1991). Some attempts were made in understanding the energy exchanges and ABL dynamics in the development of the thunderstorm over the Indian region (Tyagi et al., 2011, 2012, 2013a, 2013b; Tyagi and Satyanarayana, 2013a; Latha and Murthy, 2011) using field observations. Dalal et al. (2012) have shown the existence of organizational modes of squall-type mesoscale convective systems during pre-monsoon season over eastern India.

The mesosphere–stratosphere–troposphere (MST) radar is found to be capable of detecting return signals arising from weak fluctuations in the atmospheric refractive index (Rao et al., 1995, 1999). With certain limitations the MST technique is capable of continually observing winds, waves, turbulence and atmospheric stability over the height range of 1–100 km with excellent time and space resolution (Balsley and Gage, 1980; Hocking, 1997a, 1997b). The MST radar is a valuable tool for routine monitoring of atmospheric wind field (Gregory et al., 1979; Walker, 1979; Harper and Gordon, 1980; Gage and Van Zandt, 1981; Gage and Balsley, 1984) and is feasible for monitoring the atmospheric turbulence as well. The wind profiler is capable of monitoring lower and mid-atmospheric processes like microscale turbulence and mesoscale convection (Uma and Rao, 2009; Rao et al., 2009, 2010; Balsley et al., 1988; Dhaka et al., 2002, 2003; Cifelli and Rutledge, 1994, 1998). Previous investigations reported that large wind fluctuations in MST radar wind are mostly associated with enhanced wind and wind shear, generally seen in baroclinic systems (Rao and Kirkwood, 2005) whereas the small scale variability in vertical velocity is associated with the passage of synoptic weather disturbances (Ecklund et al., 1981; Larsen and Röttger, 1982; Sato et al., 1995; Rao et al., 1999; Dhaka et al., 2002; Kumar, 2006; Uma and Rao, 2008). Turbulence studies are made using turbulent kinetic energy (TKE), spectral widths, Signal-to-Noise Ratio (SNR) and refractivity structure constant, Cn^2 (Rao et al., 2001; Rao and Rao, 2007). Spectral widths and SNR observations indicate the intensity of turbulence and mixing depth (height of the boundary layer) in different seasons. As detailed above, only a few studies exist in the literature describing the vertical and spatial structures of turbulence and convection during the different epochs of MCS over southern peninsular India, in particular over Gadanki. The present study, therefore, focuses mainly on understanding the wind structure, turbulence transport, and convection mechanism during the passage of severe thunderstorms over Gadanki, India.

2. Data

In the present study, three thunderstorm events that occurred over Gadanki region on 25 April, 4 May and 6 June 2011 are chosen. Doppler Weather Radar (DWR)-derived reflectivity imageries are used to locate the convective systems and the duration of occurrence of the events over the study region. The MST radar data, the three spectral moments; received signal power, radial velocity, and spectral variance, are used to identify the convective cores and turbulent air parcels over Gadanki region during the thunderstorm period. Horizontal wind profiles derived from the MST radar for the duration of the thunderstorm activity are analyzed. Radiosonde observations obtained at study site are utilized for validating the derived wind profiles from the MST radar.

Micro-meteorological tower data comprises of slow response data (1 Hz) of wind speed, wind direction, temperature, relative humidity and pressure at 6 heights, 2, 4, 8, 16, 32 and 50 m, and fast response data (20 Hz) comprising of sonic anemometer (zonal, meridional and vertical wind components and sonic temperature) at 8 m.

3. MST radar system description

The Indian MST radar is located at National Atmospheric Research Laboratory at Gadanki, near Tirupati. Gadanki (13.5°N, 79.2°E; 375 m above sea level) is situated in a rural area of Chittoor district (Andhra Pradesh) in the southern part of India. The MST radar is a high-power, mono-static, coherent-pulsed Doppler radar. Indian MST radar is a highly sensitive VHF phased array radar operating at 53 MHz, with peak power aperture product of 3×10^{10} Wm^2 (Rao et al., 1995; Rao et al., 1999). The phased array consists of 1024 (32 × 32) crossed three-element antennas occupying an area of 130 m × 130 m. A total transmitting power of 2.5 MW (peak) is provided by 32 transmitters, whose output power varies from 20 kW to 120 kW.

To measure the three components of wind (zonal, meridional and vertical), a total of 4 beams were employed (two zenith and two off-vertical tilted 10° towards east and south). The radar switches alternatively between vertical and off-vertical in order to obtain high resolution samples of vertical wind along with horizontal wind and spectral width measurements. The received echo signals were sampled at interval of 300 m in the height range of 1.5 to 20.4 km and were coherently integrated. These samples are subjected to Fast Fourier Transform (FFT) for the on-line computation of the Doppler power spectra for each range bin. The off-line data processing of the Doppler spectrum includes estimation of average noise level and computation of the three radar spectral moments.

4. Quality control

4.1. MST radar data

The raw data signals received from the radar required quality controlling as it contains both noise and signal components.