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Thermodynamical and cloud microphysical response during the transition from southwest to northeast monsoon

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ABSTRACT

The thermodynamical and microphysical response during the transition from southwest to northeast monsoon season is studied. Unique mixed phase cloud observations from the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) and ground based observations from Integrated Ground Observation Campaign (IGOC), high resolution (3 km) mesoscale forecasts with the nested Weather Research and Forecasting (WRF) model are used in the study. Convective available potential energy (CAPE), liquid water path (LWP) and precipitable water (PW) increased 3 days before the onset and further enhanced with the onset of the northeast monsoon. A systematic decrease in lifting condensation level (LCL) height and increase in midlevel moisture before and during the onset period are observed, which resulted in increase in moist static energy in the midlayer for supporting deeper convection during the onset. Cloud microphysical response is noted with the mixed phase cloud observations of liquid water and ice water content. The model has simulated the mixed phase clouds in the area of detailed observations. Major cloud microphysical changes observed are (a) shallow warm clouds before the onset, (b) elevated supercooled liquid water content at the tops of clouds and (c) low ice water content during the onset period compared to subsequent periods after the onset with more ice water content.
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1. Introduction

The southwest summer (SW) monsoon season (June through September) over the Indian subcontinent has been the main focus of research while northeast (NE) monsoon season (October through December) over south peninsular India has received less attention (Kripalani and Kumar, 2004). The NE monsoon rainfall contributes about 10–20% of annual rainfall over India (Prakash et al., 2013). An extensive study on the onset and withdrawal of NE monsoon over Tamilnadu state has been carried out by Raj (1992; 1998; 2003). The withdrawal of south west monsoon is more gradual than the onset, characterized by reduction in rainfall over India. The decay of anticyclonic circulation over Tibetan Plateau and the reappearance of upper level westerly winds south of the Himalayas are also important features associated with the withdrawal (Pattanaik et al., 2015). The low-level wind over the Indian region reverses its direction from southwesterly to northeasterly during this season due to shifting of equatorial trough over southern peninsula from semi permanent orientation along the head Bay of Bengal to Ganga Nagar axis in July–August (Raj et al., 2007). The subsequent increase in rainfall over the southern peninsula is taken as the NE monsoon onset. Normal date of onset of the NE monsoon over Tamil Nadu, is around 20 October with a deviation of about 7–8 days. Peninsular India, mainly Tamil Nadu state and southeast coast of India receives about 50% of its annual rainfall from the NE monsoon rainfall (George et al., 2011).

Bunker (1967) studied about the cloud formation in the leeward side of mountain during north east monsoon using aircraft observation. He stated that mesoscale eddies or merging of small jets flowing from east in the valley along with the air flowing from north over the Arabian Sea (AS) are the possible reasons for the cloud formation. The SW and NE monsoon were studied separately by many researchers viz. Pai (2004), Rajeevan et al. (2012), Balachandran et al. (2006) etc. The excess or deficit SW monsoon rainfall is negatively correlated with NE monsoon rainfall (Dhar and Rakhecha, 1983; Selvaraj and Aditya, 2011). There have been no studies on the investigation of the cloud microphysical structure.

Zhao and Lei (2014) investigated the microphysical properties of the nimbostratus clouds associated with a north east cold vortex using airborne observations over a tropical region. Large liquid water content and cloud droplet number concentration are noted in the warm part of the cloud. Very high ice particle concentration between the temperature range of −3 °C to −6 °C associated with the super cooled cloud which contains ice particles in the form of columns, needles, aggregations and plates, which is explained by Hallett–Mossop ice multiplication process. Study conducted by Lee et al. (2014) examined the microphysical structures of a developed convective cell with in the vicinity of a terrain using a cloud resolving model. They found that the microphysical structure related with enhancements of the convective cells on the

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windward and lee side is different. Enhancement of the system on the windward side is by warm rain process caused by regional updraft due to system–terrain interaction at low altitudes and sufficient moisture supply from sea surface. Whereas on the lee side, hydrometeors increased below and above the freezing level because of terrain generated convergence and southwesterly upslope moist wind. Hou et al. (2010) analyzed the precipitating stratiform clouds (altostratus and stratocumulus clouds) using aircraft, radar and precipitation data set. They have shown that ice particles that grew at levels 4–5.5 km were dominated by depositional growth, mixed with aggregation. Ice particle habits were characterized by dendrites at −1 °C, needles at −3 °C and dendrites and irregulars at −6 °C to −9 °C.

The representation of cloud microphysical properties in model simulations remains a challenge (Morrison and Grabowski, 2007; Rajeevan et al., 2010). The diabatic heating error in the western pacific can be one of the reasons for the poor simulation of the NE monsoon in GCMs but the low-level southerly wind and moisture supply are better simulated (An et al., 2009). Weather Research and Forecasting (WRF) model predicts mesoscale features such as land sea breeze during the NE monsoon season on the west coast (Vishnu and Francis, 2014).

Indian Institute of Tropical Meteorology (IITM) has conducted a major Cloud Aerosol Interaction and Precipitation Enhancement EXperiment (CAIPEEX) under the Ministry of Earth Sciences (MoES) from 2009–2011. The aim of the experiment was to gain more knowledge on cloud–aerosol interaction and cloud microphysics in different regions of India, and response of cloud microphysics to the seeding for rain enhancement. An overview of CAIPEEX objectives and data quality is reported by Kulkarni et al. (2012). CAIPEEX phase-II second year was conducted from 2 August to 11 November 2011 at Hyderabad (Hyd; 17.45°N, 78.46°E). Hyderabad is located in the rainshadow region on the eastern side of the Western Ghats. An Integrated Ground Observation Campaign (IGOC) was conducted together with CAIPEEX-II 100 km south west of Hyderabad. Several ground based remote sensing instruments, instrumented balloon flights and instruments on meteorological tower are used in the campaign. As the experiment was carried out during 02 August to 31 October 2011, the Indian summer monsoon as well as post-monsoon period was covered. Complete withdrawal of SW monsoon and onset of NE monsoon occurred on 24 October in 2011 (All India weather summary, 2011).

In this study we try to address the thermodynamical, cloud macro- and microphysical changes during SW to NE monsoon transition period. In situ observations from several ground based remote sensing instruments and aircraft measurements are used in this study. Hourly convective parameter forecast was carried out with high resolution WRF model over the peninsular Indian region to illustrate the spatial and temporal evolution of thermodynamical and microphysical parameters. The mixed phase clouds are observed over the study region and their representation in the numerical models has significant uncertainty. The objective of the present study is (a) to exemplify the synoptic and thermodynamic changes during the transition (b) to illustrate the cloud microphysical parameters from airborne observations and (c) evaluate the model performance. The outline of the paper is as follows: the data and methods are explained in Section 2. Section 3 describes the results therein thermodynamic conditions and microphysical characteristics from observation and model simulation, followed by discussion. Section 4 deals with conclusions.

2. Data and methods

The CAIPEEX-IGOC was conducted at Mahabubnagar (MBN, 16.46°N, 77.56°E) approximately 100 km away, southwest of Hyderabad (Fig. 1). The primary data set consists of a series of in situ observations (see Table 1 with details of instruments and data) from high resolution microwave radiometer (MWR), C-band radar and aircraft. MODerate resolution Imaging Spectroradiometer (MODIS) Aqua satellite data, daily rain-gauge and satellite merged rainfall data (Mitra et al., 2009) at 0.25° resolution (http://www.imdpune.gov.in/mons_monitor/data/down_data.htm) are also used. The WRF model forecasts used in the present study is to assess the model performance with observation. To examine the evolution of NE monsoon, data for the period 20–31 October 2011 is considered i.e. few days before and after the onset. Onset of the NE monsoon is considered as zero (0) day (24 October 2011). The details of the each data set are given below.

Microwave radiometer profiler (Radiometrics Inc., USA) installed at the IGOC site, provides the vertical distribution of temperature, water vapor and cloud liquid water content at 2 min temporal resolution from surface to 10 km. Various hourly averaged convective parameters, viz. convective available potential energy (CAPE), the height of lifting condensation level (LCL), liquid water path (LWP), precipitable water (PW), equivalent potential temperature (θ_e) and cloud liquid water (CLW) above and below cloud base are calculated. The radiometer data bias was corrected with the help of radiosonde observations conducted from the same location.

The radar reflectivity datasets from C-band radar are ingested into a storm tracking technique called TITAN (Thunderstorm identification tracking analyses and now casting). The TITAN identifies the tracks of storms when it exceeds a given threshold (here, 25 dBZ). Daily average precipitation flux and maximum reflectivity are derived from radar echoes using TITAN algorithm. The columnar integrated aerosol optical depth (τ) at 550 nm and cloud optical depth (τ_c), liquid and ice cloud effective radius for the domain 15.5°N–18°N and 77.5°E–79.5°E from MODIS onboard Aqua satellite are utilized. The daily rain rate data from TRMM-IMD merged data set is extracted for the period 23–30 October 2011.

The Weather Research and Forecasting model (WRF-ARW V3.2; http://www.mmm.ucar.edu/wrf/users/) forecasts were made at 3 km resolution. The model forecasts were made at three spatial resolutions in three nested domains (27, 9 and 3 km resolution) with the outer domain covering the entire Indian subcontinent. The innermost domain covered the peninsular Indian region, which is used in the present study. Initial conditions were adopted from the Global Forecast System (GFS) forecast outputs at 1800 UTC and outer domain was updated with every 3 h forecast products. The model physics used are previously tested over the region in earlier studies (Prabha et al., 2011) and Planetary Boundary Layer is parameterized with Yosnei University (YSU) nonlocal scheme (Hong and Lim, 2006), Monin Obukov (MO) similarity scheme for the surface layer and Noah land surface scheme (Chen and Dudhiya, 2001a, b) using the updated MODIS land use dataset, WRF double moment (WDM-6) cloud microphysics, Kain Fritsch cumulus scheme in the two outer domains, Rapid Radiative Transfer Model longwave parameterization schemes were used. The 3 km domain simulation is done with cloud permitting model. Several diagnostic parameters are estimated from the model forecasted variables for every 24 hour period. Simulated WRF model parameters like CAPE, PW, LCL, LWP, water vapor mixing ratio (WVMR), surface wind and ice water content (IWC) are used for comparison with observation and also for evaluating the model performance.

The CAIPEEX aircraft measurements we use include the vertical distribution of cloud droplet number concentration (CDNC), effective radius (r_e), derived from the cloud droplet size distribution measured in situ by Forward Scattering Spectrometer Probe (FSSP) and liquid water content (LWC) measured by Hot Wire probe. We also use ice water content (IWC) estimated from Cloud Imaging Probe (CIP) and Precipitation Imaging Probe (PIP) instruments onboard the aircraft. The CIP and PIP dataset was processed by “System for Optical Array Probe (OAP) Data Analysis (*SODA*)” developed at the National Centre for Atmospheric Research (NCAR). Ice particle mass or density for single particles or sizes and habits to ice particle ensembles containing single or mixed particle habit was estimated based on the method developed by Heymsfield et al., (2004). Aerosol concentrations measured by Passive Cavity Aerosol Spectrometer Probe (PCASP) are also used in the analysis. These measurements were made at an interval of 1 s

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