Analysis and Prediction of Thunderstorms over Andhra Pradesh using INSAT 3D and MODIS Satellite Data

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ABSTRACT

Predictability of thunderstorms over Andhra Pradesh (India) using MODIS and INSAT satellite data has been attempted. Andhra Pradesh region is vulnerable to severe local storms during the hot period of pre-monsoon season. Apart from the conventional radiosonde observations available for a long time, satellite data of recent times provide atmospheric data useful for prediction of thunderstorms. Thermodynamic variables and stability indices based on physics have been identified to provide guidance to convection and thunderstorm activity. The present study pertains to the derivation and analysis of the thermodynamic variables such as Lifting Condensation Level (LCL), Level of free Convection (LFC) and indices such as K Index (KI), Lifted Index (LI), Total Totals Index (TTI), Convective available potential energy (CAPE) and Convective Inhibition (CIN) associated with severe convection and non-convection over Andhra Pradesh during May, 2017.

Daily gridded rainfall at 0.5 degree resolution over AP for May 2017 have been examined to identify the thunderstorm occurrence days as evinced through rainfall > 2cm on the meso - spatial scale. Further, INSAT 3D images and brightness temperature at 30 minute interval for the identified thunderstorm days were analyzed to identify the onset, development and decay of convection. The results show that MODIS and INSAT 3D satellite data based stability indices have all shown values favouring convection in respect of four thunderstorm events and two clear non-convective regimes. The indices values clearly delineate the convective and non-convective regimes and indicate thresholds. Results of this study indicate predictability of convection evolution leading to thunderstorm activity using satellite data which plays an important role in disaster management.

Keywords:

1. Introduction

Rainfall is the one weather variable, which has immense social importance. Convection is the physical process for the occurrence of rainfall. In the tropical regions, convection is produced due to thermodynamic conditions (i.e.) strong surface heating in summer causes warm air rising as a consequence of parcel-environment temperature difference or lapse rate. Several types of convection occur and most of them produce rainfall. Dust storms are known to occur in dry environment due to heating at the surface, wherein there will be strong vertical motions prevail but with no rainfall (Bergeron, 1965) (Bader et al (1977)) (Demko et al. 2010). In contrast, a thunderstorm has rain shower associated with thunder to be heard and lighting to be seen. Thunderstorms are

Table 1 .Thunderstorm induced damage/loss in India

Date	Weather event	Region	Damage/ Loss(INR)
17/3/1978	Tornado	New Delhi	1.0 Crore
02/04/2002	Hailstorm	Telangana	1550 Crore
12/03/2003	Hailstorm	West Bengal	99.2 Crore
15-30/04/2004	Hailstorm	Andhra Pradesh	5.16 Crore
13/4/2010	Thunderstorm	East India	600 Crore
2/6/2014	Thunderstorm	New Delhi	N/A
18/3/2015	Hail storm	Nagpur	10000 Crore
7/4/2015:	Hail storm	Bareilly	1100 Crore
23/4/2015	Thunderstorm	Tripura	8.0 Crore
29/4/2015	Thunderstorm	Haryana	1092 Crore
2/03/2016	Thunderstorm	Ahmedabad,Gujarat	N/A

responsible for severe weather due to the occurrence of hail and downburst as they often cause damage to property and loss of life. The different convective weather systems are tropical cyclones, squall lines, Mesoscale Convective Complexes (MCCs), polar lows, and extra-tropical fronts.

As per the thermodynamics, thunderstorms emanate due to rise of warm air over the heated land masses inducing convection. In India, peak thunderstorm activity occurs during the months March-April-May (i.e.) the pre-monsoon or hot season and are mostly confined to Jharkhand, Bihar, Sub-Himalayan West Bengal, Gangetic West Bengal, Odisha, Chhattisgarh, Assam and adjacent states to East Madhya Pradesh, East Vidarbha and adjoining Andhra Pradesh, Southwest Peninsular India, and Northwest India outside Rajasthan. The number of thunderstorm days is about 6-8 in March and increase to 14-16 during May. In the pre-monsoon season, strong convective activity develops over Jharkhand and the convective systems move southeast towards Bengal that are commonly known as “Norwesters” or “Kal-Baisakhi” in Gangetic plains and as “thunderstorms” in the south. Thunderstorms are considered as natural disasters as lightning kills humans and cattle, hail inflicts extensive damage to agriculture and property, heavy rainfall leads to flash floods and strong gusty winds affect power infrastructure and aviation.

In the southern parts of India, Andhra Pradesh (AP) experiences severe thunderstorms during the pre-monsoon season and more during May. These thunderstorms are known to have caused extensive damage in the region of AP and neighbourhood. During the current year of 2017, lightning killed five persons in

Anantpur district on 14 May, 2017; 2 persons and 70 sheep in Kurnool district, and a woman in West Godavari district, all on 27 May, 2017. Besides the fatalities, banana plantations and drum stick trees were extensively damaged in Kurnool district on 27 May, 2017 due to hail. Some of the thunderstorm damage statistics as compiled by Yasvant Das (2015) are given in Table 1. The information reveals the possible extent of damage that could be caused by thunderstorms over India, to be varying from few crores to thousands of crores of Indian rupees. The increase of damages may be attributed to the increase of urban and industrial infrastructure that are vulnerable to the severe storm disasters. The above described background information brings out the importance of understanding the characteristics of thunderstorms of the study region, and their predictability to help disaster mitigation and management. Due to the societal impacts, there is growing demand for high resolution mesoscale weather information from the sectors of transport, including aviation, agriculture, hydrology and social welfare. Current observational network and synoptic methods of forecasting are capable only to provide broad and general information. More precise information require observations at high spatial and temporal resolution to characterise mesoscale atmospheric phenomena such as thunderstorms which could be accomplished with the use of observations from Doppler weather radars, Lidars, satellites, wind profilers, aircraft and meso-network observatories.

Several methods have been suggested for the prediction of thunderstorms; most of them are based on synoptic and thermodynamic methodologies. Although atmospheric models are widely used for weather prediction, inadequate mesoscale observations to produce relevant mesoscale initial conditions (especially of moisture and temperature) for model prediction put a constraint on their application. (Kober and Tafferner, 2009, Rajeevan et al., 2010 and Madhulatha et al 2013). In India, observations from radars operating at a wavelength of 3 cm to detect thunderstorms were started in 1950s. A number of radiosonde and radar based studies by Koteswaram and Srinivasan (1958); and many others contributed to thunderstorm research in India. Raghavan et al. (1983)

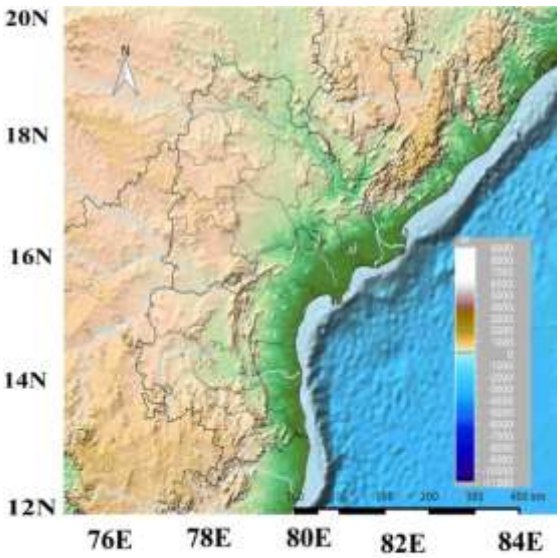

Figure 1: Study region of Andhra Pradesh

Demonstrated the application of digital radar for the assessment and short period forecasting of precipitation using radars. Based on Runway Visual Range (RVR), surface wind and radar observations at Palam airport, Joseph et al. (1980) developed a physical model of the "Andhi", convective dust storms of Northwest India. In the early seventies, a set of 10 cm radars, capable of tracking up to 400 km were set up along the Indian coasts mainly to detect and track tropical cyclones. Observations from these radars were used to identify the convective patterns inside a Bay of Bengal cyclone (Gupta and Mohanty, 1997). Since 2013, satellite data from geostationary and polar orbiting satellites have been providing valuable data of cloud imagery and atmospheric soundings. The cloud imageries from the Indian geostationary satellite INSAT (Indian National Satellite System) have the capability of continuously observing the evolution of clouds from cumulus to synoptic scale. The cloud imageries, produced at an interval of 30 min, are effective to capture convective scale interactions that initiate deep convection. For e.g. the presence of Messiah, a characteristic feature associated with intense thunderstorms, is generally seen as an arc-shaped cloud boundary in the satellite pictures. Kalsi and Bhatia (1992) studied the development of thunderstorm complexes in a weakly forced environment with the help of INSAT imageries.

For predicting the thunderstorms, several indices have been developed based on thermodynamic variables. Studies in the past, mainly used vertical temperature and humidity profiles from radiosonde data for computing the indices (Rao and Raman, 1983, Tyagi, 2007, Koteswaram and Srinivasan, 1958, Mukhopadhyay *et al.* 2003).

The advent of satellite era and remote sensing data from satellites has provided an opportunity to use satellite derived indices for the prediction of thunderstorms. Data from MODIS TERRA and AQUA satellites have become available since 1999 and 2002 respectively, and a few studies on thunderstorms using MODIS data have been attempted (Jayakrishnan and Babu, 2014). Jayakrishnan and Babu (2014) used the MODIS satellite derived stability indices such as K Index (KI) , Lifted Index (LI) , Total Totals Index (TTI) to identify their thresholds as <-4 for LI, 35-40 for KI, 50-55 for TTI for convective formation over south peninsular India. The main constraint on the use of MODIS data is that its pass takes 1-2 days and so any point on the earth could be explored at best once in a day. In contrast, INSAT 3D launched in July, 2013 provides data through imagery and sounder every 30 minutes and at 10 km resolution covering the Indian subcontinent which enables continuous monitoring of the atmosphere for the generation of convective activity. IMSAT 3D us being used by several national agencies (IMD etc) and research groups mainly for data assimilation and this study aims to bring forth the use of this data in thunderstorm prediction. Considering the importance of understanding and prediction of severe local storms in the region of India and neighbourhood, a scientific program "Severe Thunderstorm Observation and Regional Modelling (STORM)" has been initiated by the Government of India, of which special field observation experiments have been envisaged and executed. The "STORM"

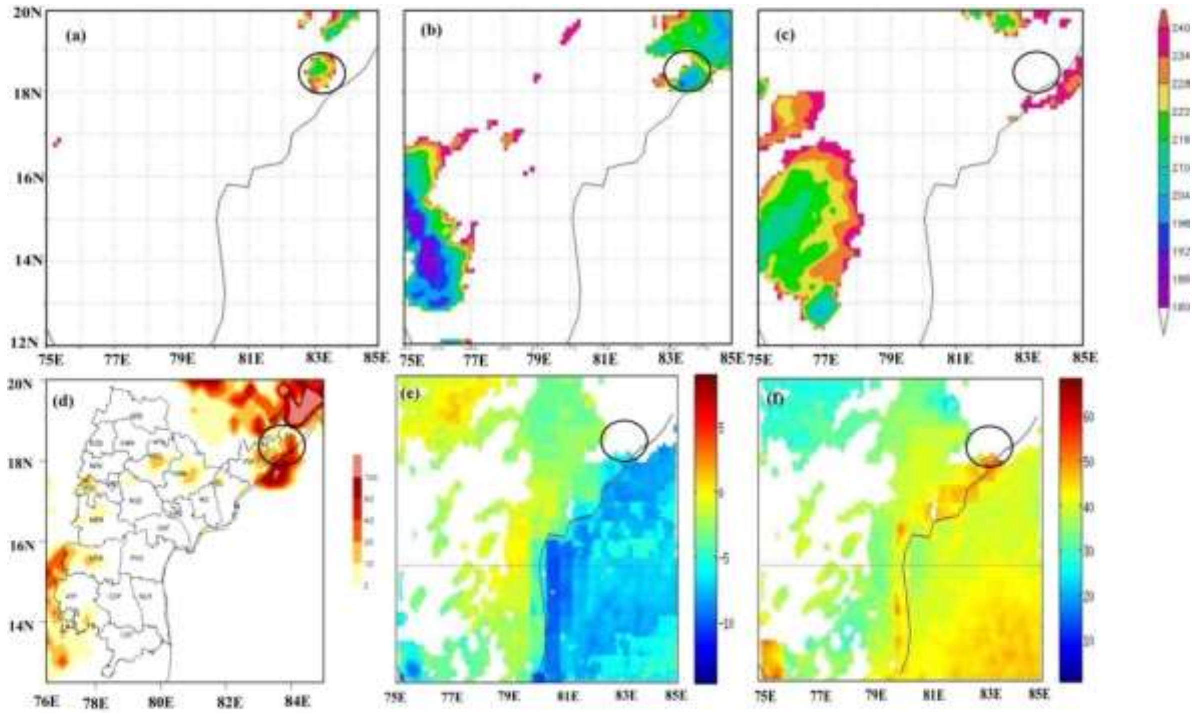

Figure 2: (a)–(c) Spatial distributions of BT (K) (a) before convection, (b) at peak of convection, (c) after convection. (d) – (f) spatial distributions of (d) Rainfall (mm), (e) LI (f) TPW (mm) derived from INSAT-3D Sounder satellite; all for May 6,2017

program has generated valuable data in the Indo-Gangetic plains which is now being used by several research groups.

2. Data and Methodology

2.1 Data

The present study was carried out over the area covering Andhra Pradesh extending from 12-20 N and 75-85 E. The following data sets were used for analysis.

(a) INSAT-3D is an advanced weather satellite of India, which is a multipurpose geosynchronous spacecraft with the main meteorological payloads of imager and sounder with the chief objective of providing storm disaster warning to protect life and property. INSAT-3D imager has imaging capability in six different channels, one in visible and five in infrared. The visible imager (VIS) channel operates in 0.52 – 0.72 μ and the five infrared channels are in short wave infrared (1.55 – 1.70 μ), Mid wave infrared (3.80 – 4.00 μ), water vapor (6.50 – 7.00 μ), and in two thermal infrared (TIR) channels. The imaging system has the capability to provide night time pictures of low clouds and fog. The data from INSAT-3D are available at http://www.mosdac.gov.in/.

For the present study, “Level1 imager L1” and “Level2 sounder L2 data” are downloaded and subject to filtering to confine to the data falling within the study domain of Andhra Pradesh.

Table 2. MODIS and INSAT 3D derived Stability Indices on 06 May 2017

Stability Indices	Srikakulam Region		
	MODIS-TERRA 0500 UTC	MODIS-AQUA 0805 UTC	INSAT 3-D Sounder 1200 UTC
Lifted Index (K)	2.24	-8.98	-8.1738
K Index (K)	285.41	319.71	330.6
Total Precipitable Water (mm)	38.61	53.46	55.36
Total Total index (K)	31.7	56.93	53.9

The L1B data, at 10 km resolution, is used to obtain brightness temperature maps using the Fortran code provided by Space Applications Centre (ISRO). The brightness temperature maps are analysed to identify the occurrence of a thunderstorm system. The stages of start, peak and dissipation are identified. Similarly Level2 L2B product data, at 10 km resolution, from the INSAT-3D Sounder Satellite were extracted. we have computed the stability indices from T,q profiles obtained from MODIS. From this profiles we computed dewpoint temperature profile using matlab program developed by the authors, to study the occurrence of convective System.. Using temperature and dew point temperature profiles we have computed stability indices.

(b) Moderate Resolution Imaging Spectro-radiometer (MODIS) data from all the passes of TERRA and AQUA satellites on the days of study were downloaded from the wbsite https://modis.gsfc.nasa.gov/data/. The MODO7 and MYDO7 products from MODIS-TERRA and MODIS-AQUA satellites, at 10 km resolution, are analysed. The parameters of Lifted Index (LI), K Index (KI), Total Totals Index (TT), and Total Precipitable Water (TPW) were computed using a MATLAB program developed by the authors. In addition, the vertical profile of temperature, dew point temperature and specific humidity were also derived and used to derive the values of CAPE, CIN, LCL, LFC, CCL and convective temperature.

(c) India Meteorological Department (IMD) gridded daily rainfall data for the Indian subcontinent at 0.5 degree resolution for May 2017 has been collected from http://imdpune.gov.in/Seasons/Temperature/gpm. The data has been used to identify the rainy days over AP region during May 2017. Specifically isolated rainfall were coincident with thunderstorm occurrences.

2.2 Methodology

The computational aspects of the different indices that have considered for identification of convection from the INSAT-3D and MODIS data are briefly presented here.

(i) K Index (KI): The K Index is determined by using the air and dew point temperatures at different levels of the atmosphere using the formula (George 1960):

KI = (T850 – T500) + Td850 – (T700 – Td700)

where T is the air temperature; Td is the dew point temperature. The values of KI represent the stages of convection, higher the value higher is the probability of thunderstorm occurrence, as given below. KI values higher than 293 K denote the possibility of thunderstorm occurrence.

K index (KI)	Thunderstorm Probability
<288	0%
288-293	<20% unlikely
294-298	20-40% isolated thunderstorm
299-303	40-60% widely scattered thunderstorms
304-308	60-80% widespread thunderstorms
309-313	80-90% numerous thunderstorms
>313	>90% chance for thunderstorms

(ii) Total Totals Index (TTI)

The total totals index is derived from the temperature lapse rate between 850 and 500 hPa levels and the moisture content at 850hPa. TTI value higher than 44 indicates thunderstorm occurrence. This index is actually a combination of the vertical totals and cross totals, which are defined as follows:

Cross totals, CT = Td850 – T500

Vertical totals, VT = T850 – T500

Total totals, TT = CT + VT = T850 + Td850 – 2T500

The risk of severe weather activity is defined as follows:

TT index (K)	Thunderstorm Probability
44 – 45	Isolated moderate thunderstorm
46 – 47	Scattered moderate / few heavy thunderstorms
48 – 49	Scattered moderate / isolated severe thunderstorms
50 – 51	Scattered heavy / few severe thunderstorms and isolated tornadoes
52 – 55	Scattered to numerous heavy / few to scattered severe thunderstorms / few tornadoes
>55	Numerous heavy / scattered severe thunderstorms and scattered tornadoes

(iii) Lifted Index (LI)

This is an index that is dependent on the stability of the lower half of the troposphere. LI values lower than -2 are indicative of thunderstorm occurrence (Galway 1956).

Lifted index (LI) = $T_{500} - T_{parcel}$

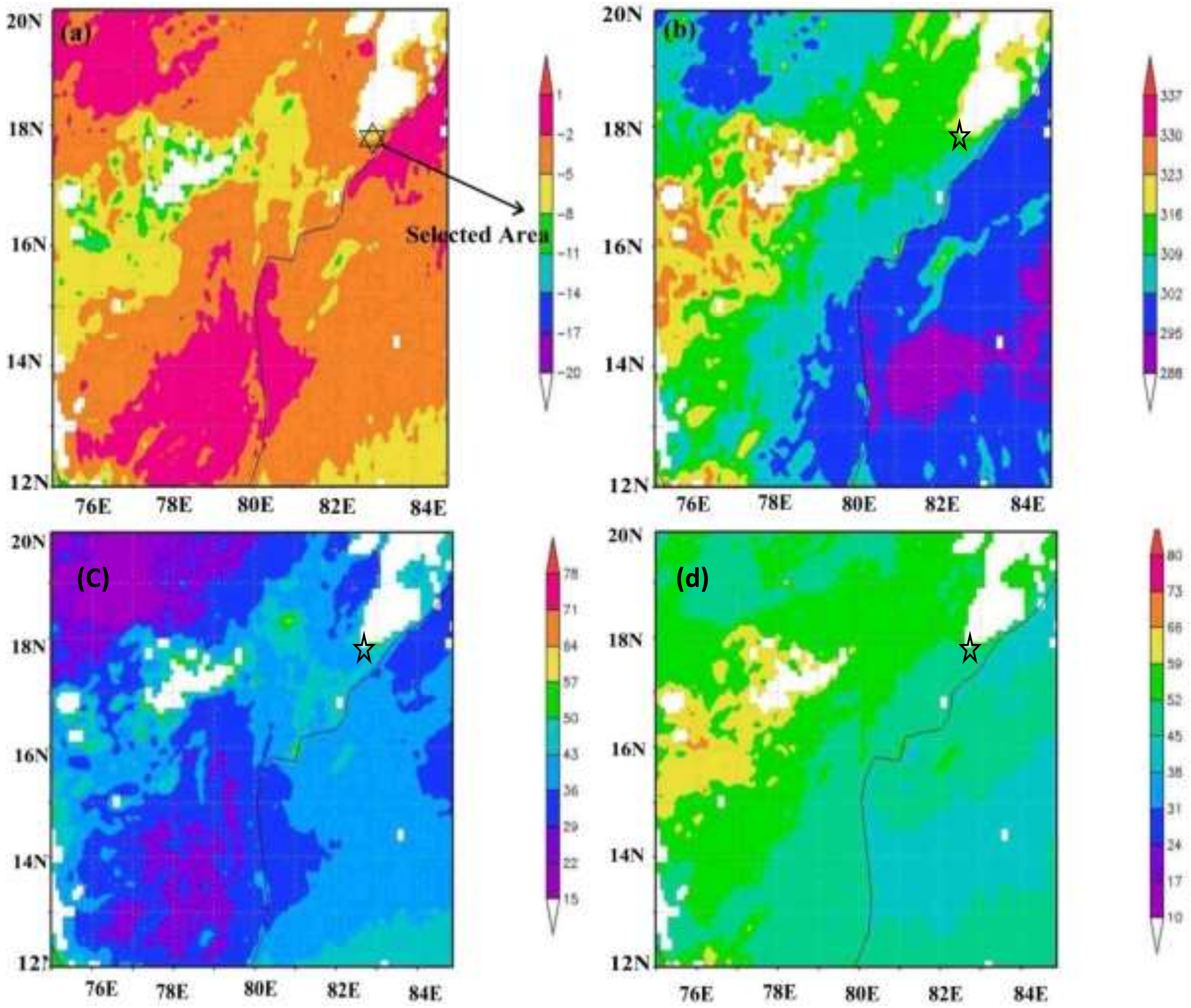

Figure 3: Spatial distributions of (a) LI (b) KI (c) TPW(mm) (d) TTI; all derived from MODIS-AQUA satellite for May 06, 2017.

Lifted index (K)	Air mass Thunderstorm Probability
> 2	No significant activity
0 < LI < 2	Thunderstorms possible with other source of lift
-2< LI <0	Thunderstorms possible
-4< LI <-2	Thunderstorms more probable, some severe
LI <-4	Severe thunderstorms possible

(iv) Convective available potential energy (CAPE)

CAPE is defined as (Mon- crieff and Green 1972, Kunz 2007)

$$CAPE = \int_{Z_f}^{Z_n} g[\frac{T_{v,parcel} - T_{v,env}}{T_{v,env}}]\, dz$$

Where $T_{v,parcel}$ and $T_{v,env}$ stands for the virtual temperature of the parcel and environment respectively. Z_f and Z_n are the levels of free convection and neutral buoyancy.

The value of CAPE can be interpreted for occurrence of thunderstorms as:

<300	little or no convective potential
300 to 1000	weak convective potential
1000 to 2500	moderate convective potential
>2500	strong convective potential

(v) Convective Inhibition

CIN is defined as

$$CIN = \int_{Z_{bottom}}^{Z_{top}} g\left[\frac{T_{v,parcel} - T_{v,env}}{T_{v,env}}\right] dz$$

where Z_{top} and Z_{bottom} denote the level of free convection and ground surface.

0 to 25 J/kg	weak inhibition
-25 to -50 J/kg	Moderate
-50 to -100 J/kg	large inhibition

The two parameters that represent convection formation in the atmosphere, namely the Lifting Condensation level (LCL) and the Level of Free Convection are generally computed using Tephigram.

(vi) Lifting Condensation Level (LCL) is the pressure level at which a parcel, when lifted adiabatically, becomes saturated (i.e. temperature of the parcel reaches its dew point temperature). The cloud base generally occurs at the LCL. Below the LCL, the lifted parcel cools at the Dry Adiabatic Lapse Rate (9.8 C/km) and above this point the parcel cools at the Saturated Adiabatic Lapse Rate (~5 C/km).

(vii) Level of Free Convection (LFC) is the pressure level at which a parcel of air, lifted dry adiabatically till saturation and then moist diabatically, would first attain buoyancy (warmer than its surroundings).

The height difference between LCL and the LFC indicate the convection atructure, smaller the difference deeper the convection.

3.0 Results and Discussion

The gridded daily rainfall data at 0.5 degree (~50 km) spatial resolution for the study region of AP is analysed for the period 1 to 31 May, 2017. From the analysis of daily rainfall data and comparison with thunderstorm reports, four good cases of convection have been picked up (May06, 2019; May 08, 2019; May 09, 2019; May 21, 2019)and satellite data pertaining to the four cases have been collected and analysed. The study region is shown in figure 1. In addition, two days of no-convection (May 05, 2019; May 10, 2019) are also analysed to facilitate comparison of the different indices on convective and non-convective days. Results of the four cases of convection and two non-convection are presented as follows:

3.1 Case 1 (06 May 2017)

Date	06 May 2017
Area of Event	Srikakulam Region
Latitude & Longitude	18.2N ; 83.3E
Coldest CCT	192 - 204 K
Peak time	1200 UTC

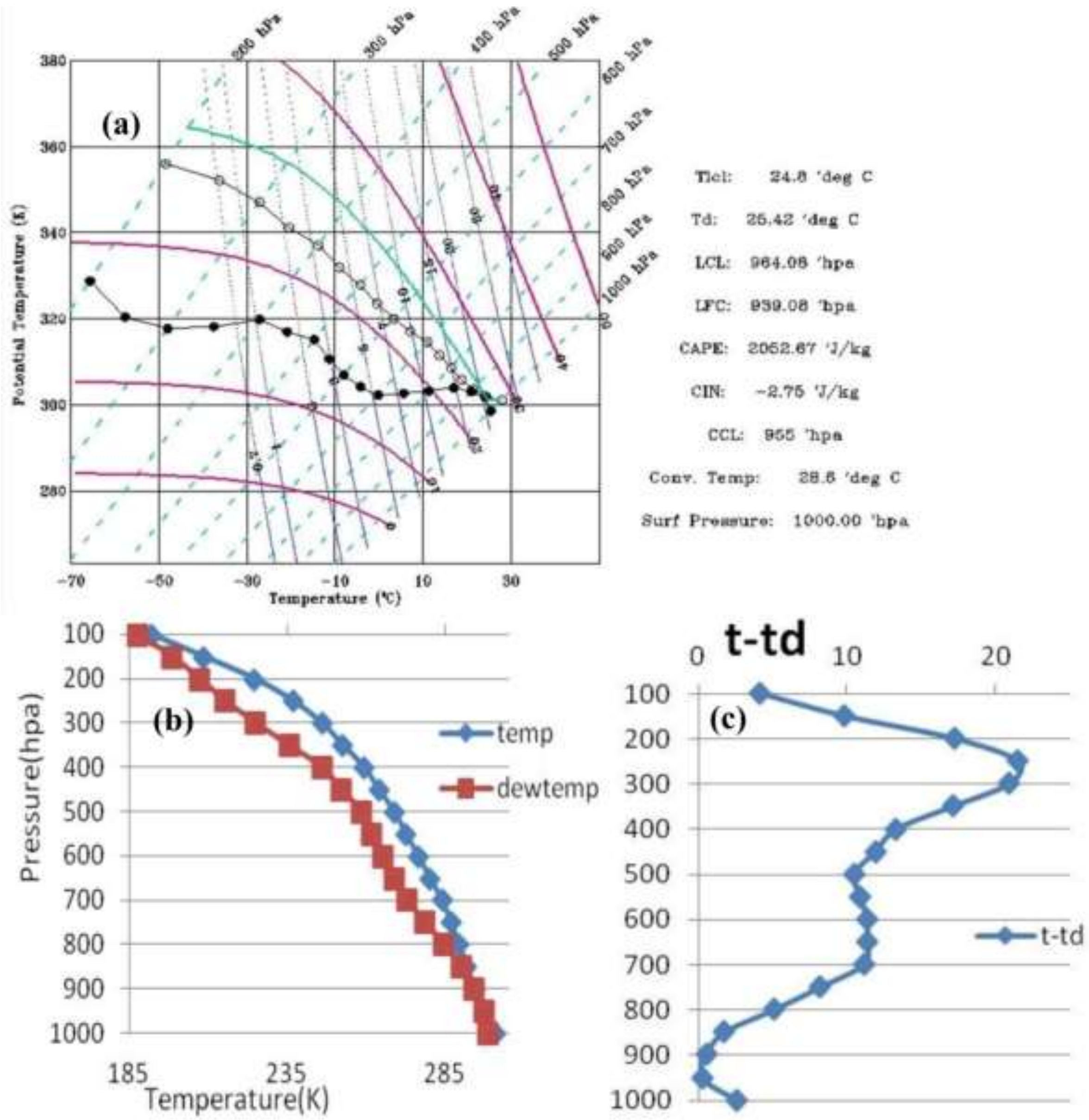

Figure 4: (a) Tephigram with T and Td (b) Vertical profiles of T and Td interpolated at 50 hPa interval (c) Dew point depression; all derived from MODIS-AQUA satellite for May 06, 2017 over Srikakulam region.

INSAT-3D brightness temperature (BT) data at half-hour interval are analysed and examined to identify the presence of mesoscale convective system (MCS). The BT values have shown no development of the MCS till 0800 UTC. Later, the MCS intensified into a strong convective system over Srikakulam region at 1200 UTC. At this time, the MCS was at its peak stage with the BT values of 192-204K. the MCS started dissipating slowly from 1300 UTC, completely dissipated by 1600 UTC. The BT values at the peak time, before and after clearly explain the development and dissipation of MCS. The decrease of BT values correspond to development of MCS associated with intense rainfall (Figure 2). The LI and TPW values derived from INSAT 3D are given in Table 2. For this event, the data from MODIS TERRA pass at 0500 UTC (nearly 7 hours before the peak of MCS) and the UTC AQUA pass at 0805 UTC (nearly 4 hours before the peak of MCS) as available are analysed. It was observed that the MODIS-AQUA 0805 UTC pass had shown good threshold values indicative of the MCS. The values of different indices over Srikakulam region indicate the presence of a severe MCS and with a very high probability of heavy rainfall and thunderstorm activity. The encircled region shows the locality of the MCS, and the presence of white patch within this circle is due to intense cloudiness which masks out MODIS data in this region. However the relatively higher values around the cloudy region denotes MCS activity within. The values of different indices at the core of the MCS are given in Table 2.

Temperature and Humidity profiles at fourteen isobaric levels derived from MODIS were plotted and examined at different latitudes and longitudes surrounding the region of the MCS event. However, only one image typical to the event is shown. The profiles from MODIS are able to elucidate the MCS development. The vertical profiles of temperature and Humidity profile, drawn over Srikakulam (17.87N, 82.79E) region are shown in **Figures 3 & 4**. The values of T and Td are obtained at every 50 hPa interval by interpolation and plotted. The Tephigram shows that the dew point depression is around 23K at 1000hpa, decreases upward reaching 0K at 700 hPa, then increased to 15K at 400 hPa and decreases to 9K at 200 hPa. This indicates the presence of moist air between 1000-800 hPa and dry air lying above between 600-100 hpa indicating a very unstable atmosphere at this location. The computed values of LCL is 975.80 hPa; CCL is 825 hPa; and LFC is 760.8 hPa. The difference between LCL & LFC is ~215 hPa which is indicative of formation of thunderstorms and MCS within next 3hrs (https:/www.weather.gov/source/zhu/ZHU_Training_Page/convective_parameters(/Sounding_Stuff/MesoscaleParameters.html). The values of CAPE and CIN are 2970.06 and -192.31J/Kg respectively which are again favourable to formation of MCS, as is generally noted that CAPE higher than 2500 J/Kg denote atmospheric instability and CIN value less than -100 J/Kg indicates smaller inhibition (Table 6).

3.2 Case 2 (08 May 2017)

Date	08 May 2017
Area of Event	Visakhapatnam Region
Latitude & Longitude	17.5N ; 83E
Coldest CCT	180 - 210K
Peak time	1100 UTC

INSAT-3D brightness temperature (BT) data, (Figure 5) indicates the BT values reducing from 240 at 0800 UTC to 192 K at 10 UTC, which indicates the development of the MCS from 0800 UTC reaching a peak stage at 1100 UTC. Later, the BT values started increasing indicating dissipation from 1300 UTC. The

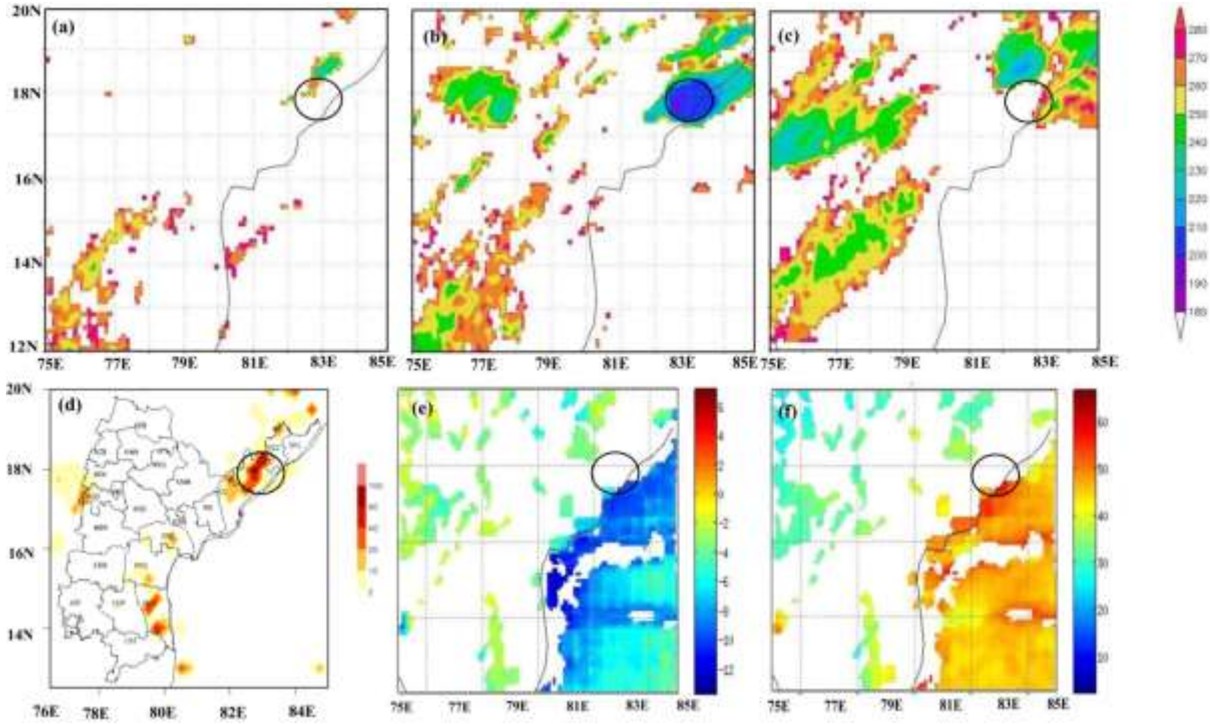

Figure 5: (a)–(c) Spatial distributions of BT (K) (a) before convection, (b) at peak of convection, (c) after convection. (d) – (f) spatial distributions of (d) Rainfall (mm), (e) LI (f) TPW (mm) derived from INSAT-3D Sounder satellite; all for May 8,2017

Table 3. Stability Indices on 08 May 2017

Stability Indices	Visakhapatnam Region		
	MODIS-TERRA 0450UTC	MODIS_AQUA 0800UTC	INSAT 3-D Sounder 1200 UTC
Lifted Index (K)	9.81	-7.8	-10.5737
K Index (K)	291.14	325.4	327.2
Total Precipitable Water (mm)	35.59	43.44	52.769
Total Total index (K)	14.59	62.27	59.3

MCS completely dissipated by 1430 UTC. The peak stage correspond to a strong development of MCS with intense rainfall. MODIS data based stability Indices for 0450 UTC TERRA pass i.e. nearly 7 hours before the peak of MCS and for 0800 UTC AQUA pass i.e. nearly 4 hours before the peak of MCS are studied for this event. MODIS-AQUA 0800UTC pass was showing good threshold values for convective system. These values over Visakhapatnam region indicate a severe MCS and a very high chance for severe rainfall and thunderstorm activity (Figure 6 and Table 3). Temperature and Humidity profiles derived from MODIS measurement at fourteen isobaric levels (MODIS measures at twenty isobaric levels) were plotted at Visakhapatnam (17 N, 83.3E)

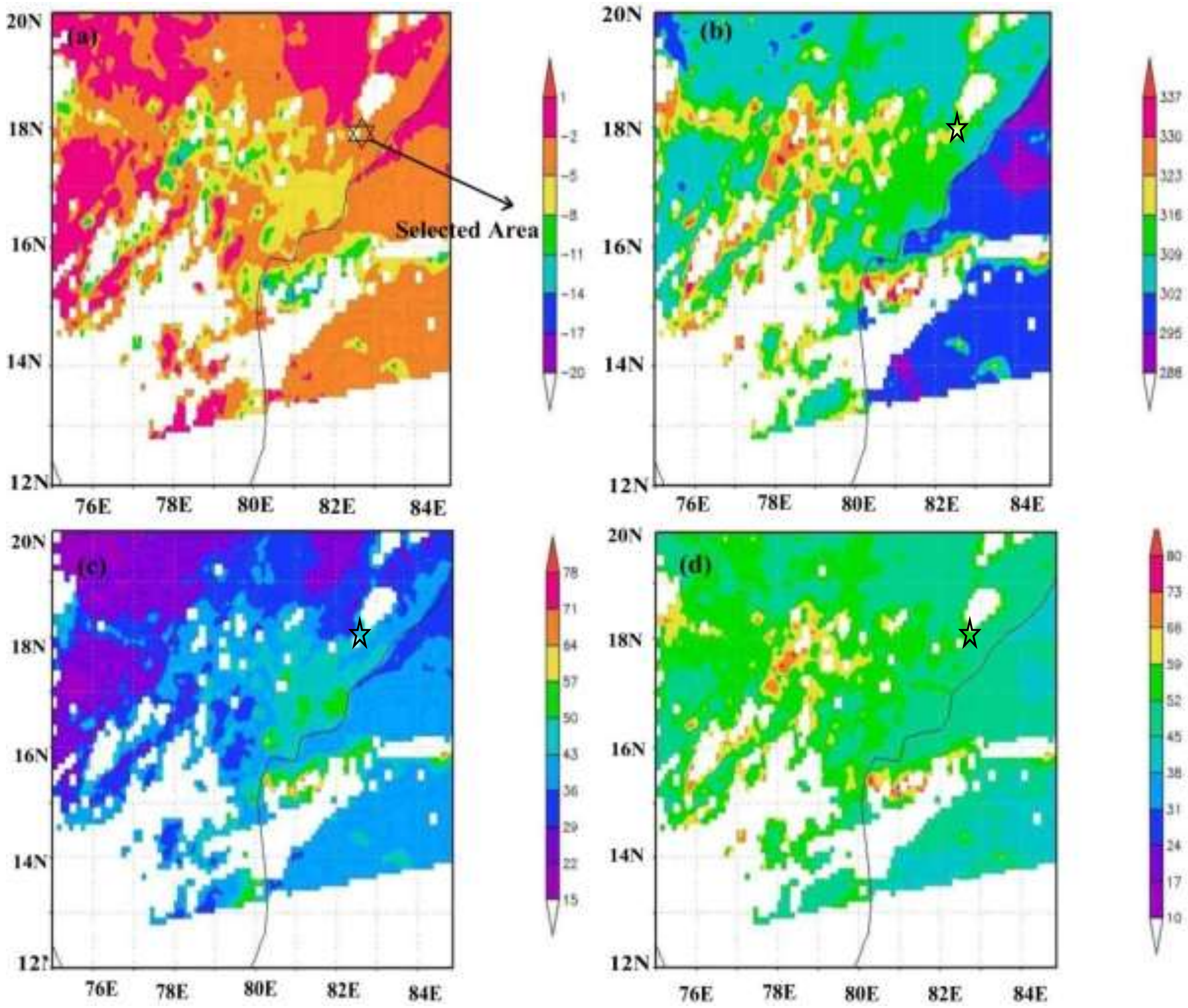

Figure 6: Spatial distributions of (a) LI (b) KI (c) TPW(mm) (d) TTI; all derived from MODIS-AQUA satellite for May 08,2017.

corresponding to the MCS event. The profiles from MODIS are able to elucidate the MCS development. The dew point depression is around 8K at 1000hpa, reduced to 0K at 850 hPa and it increased to 9K at 700 hPa and then started decreasing. This indicates the presence of moist air between (1000 hPa – 800 hPa) and a dry air lying above this moist air from (600 hPa-100 hPa) indicating very unstable atmosphere at the location. The computed LCL is 928.73 hPa; CCL is 885 hPa and LFC is 858.73 hPa. The difference between LCL and LFC is 70 hPa which is very small and helpful to rapid formation of thunderstorms and MCS within the next 2 hours. The CAPE and CIN values are 2876.57J/Kg and -27.73J/Kg respectively over Visakhapatnam which indicate thunderstorm occurrence (Figure 7, Table 6).

3.3 Case 3 (09 May 2017)

Date	09 May 2017
Area of Event	Guntur Region
Latitude & Longitude	15.5N ; 79.1E
Coldest CCT	180 - 210 K
Peak time	1200 UTC

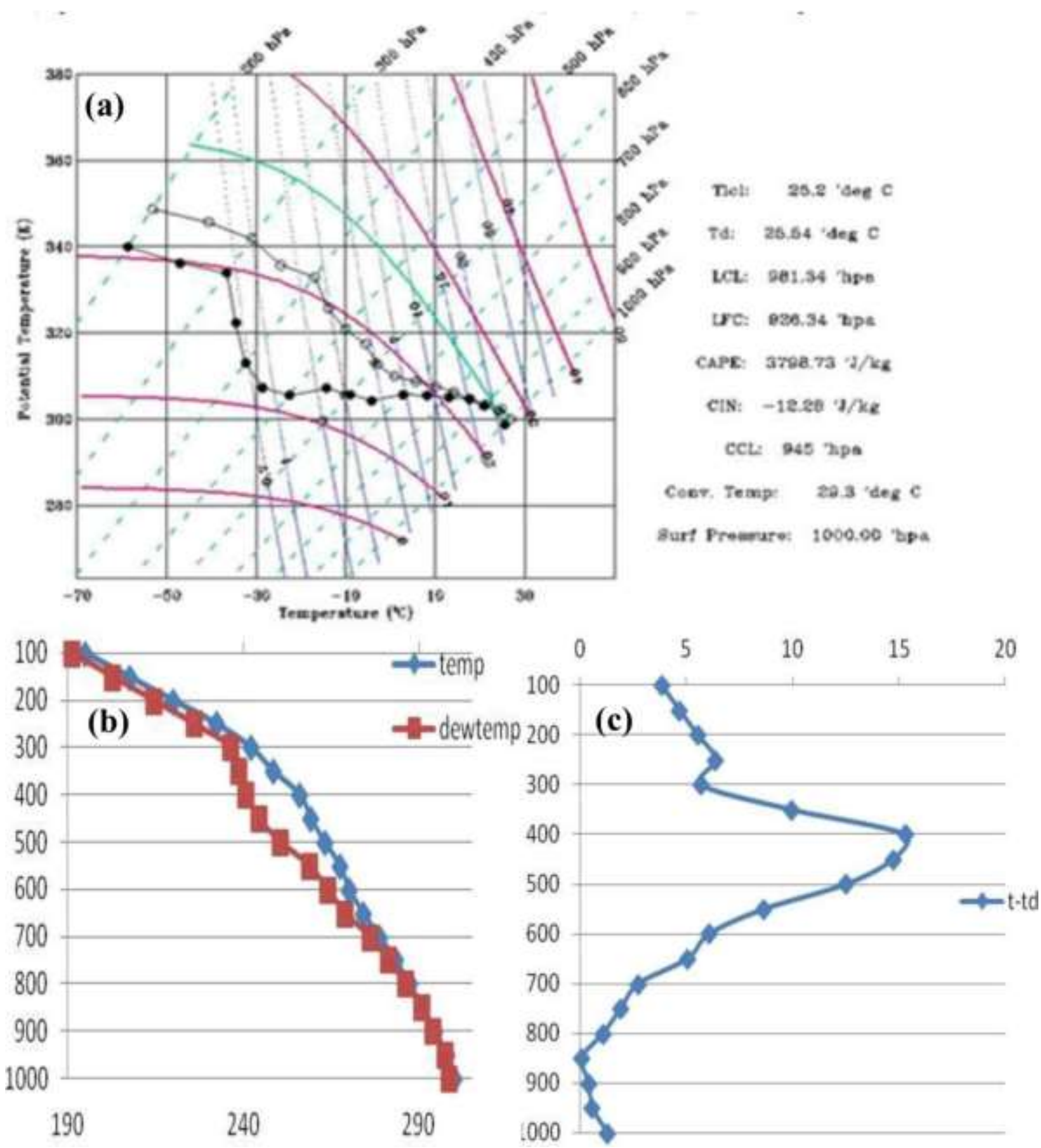

Figure 7: (a) Tephigram with T and Td (b) Vertical profiles of T and Td interpolated at 50 hPa interval (c) Dew point depression; all derived from MODIS-AQUA satellite for May 08, 2017.

INSAT-3D brightness temperature (BT) data have shown no indication of around 0800 UTC. Later, intense MCS was observed over Guntur region at 1200 UTC, with the BT values of 192-210 K indicative of strong convection. Later, it started to dissipate from 1300 UTC and completely dissipated by 1700 UTC (Figure 8).

MODIS stability Indices from TERRA pass for 0530 UTC (nearly 6 and half hours before the peak of MCS) and for AQUA pass at 0840 UTC (i.e. nearly 4 hours before the peak of MCS) are studied. MODIS-AQUA pass has shown values above the threshold indicative of MCS. The values of different stability indices are shown in Table in which contrasting values

Table 4. MODIS Stability Indices on 09 May 2017

Stability Indices	Visakhapatnam Region		
	MODIS-TERRA 0535 UTC	MODIS-AQUA 0840 UTC	INSAT 3-D Sounder 1200 UTC
Lifted Index (K)	10.14	-6.69	-5.27
K Index (K)	288.17	317.49	332.0
Total Precipitable Water (mm)	36.6	52.25	45.43
Total Total Index (K)	10.28	55.63	57.6

Table 5. MODIS Stability Indices on 21 May 2017

Stability Indices	East Godavari Region		
	MODIS-TERRA 0600 UTC	MODIS-AQUA 0900 UTC	INSAT 3-D Sounder 1000 UTC
Lifted Index (K)	12.76	-7.11	-6.34
K Index (K)	295.52	323.49	328.3
Total Precipitable Water (mm)	23.53	62.49	51.11
Total Total index (K)	26.83	50.25	62.0

Table 6. MODIS & INSAT-3D Satellite Stability Indices.

MODIS Satellite						
Stability Indices	Case 1 – May 06, 2017	Case 2- May 08, 2017	Case 3- May 09, 2017	Case 4-May 21, 2017	Case 5- May 05, 2017	Case 6- May 10, 2017
Lifted-Index	-8.98	-7.8	-6.69	-7.11	0.92	0.39
K-Index (K)	319.71	325.4	317.49	323.49	293.62	283.23
TPW (mm)	53.46	43.44	52.25	62.49	32	28.63
TTI (K)	56.93	62.27	55.63	50.25	40.56	36.85
LCL-LFC (hPa)	25	70	100	55	175	150
CAPE (J/Kg)	2052	2876.57	2666.81	3798.73	692.20	1386.25
CIN (J/Kg)	-2.75	-27.73	-44.33	-12.28	-83.55	-57.18
INSAT-3D Satellite						
Lifted-Index	-8.17	-10.57	-5.27	-6.34	2.13	0.26
K-Index (K)	330.6	327.2	332.0	328.3	296.5	285.16
TPW (mm)	55.36	52.77	45.43	51.11	29.71	34.61
TTI (K)	53.9	59.3	57.6	62.0	42.35	38.96

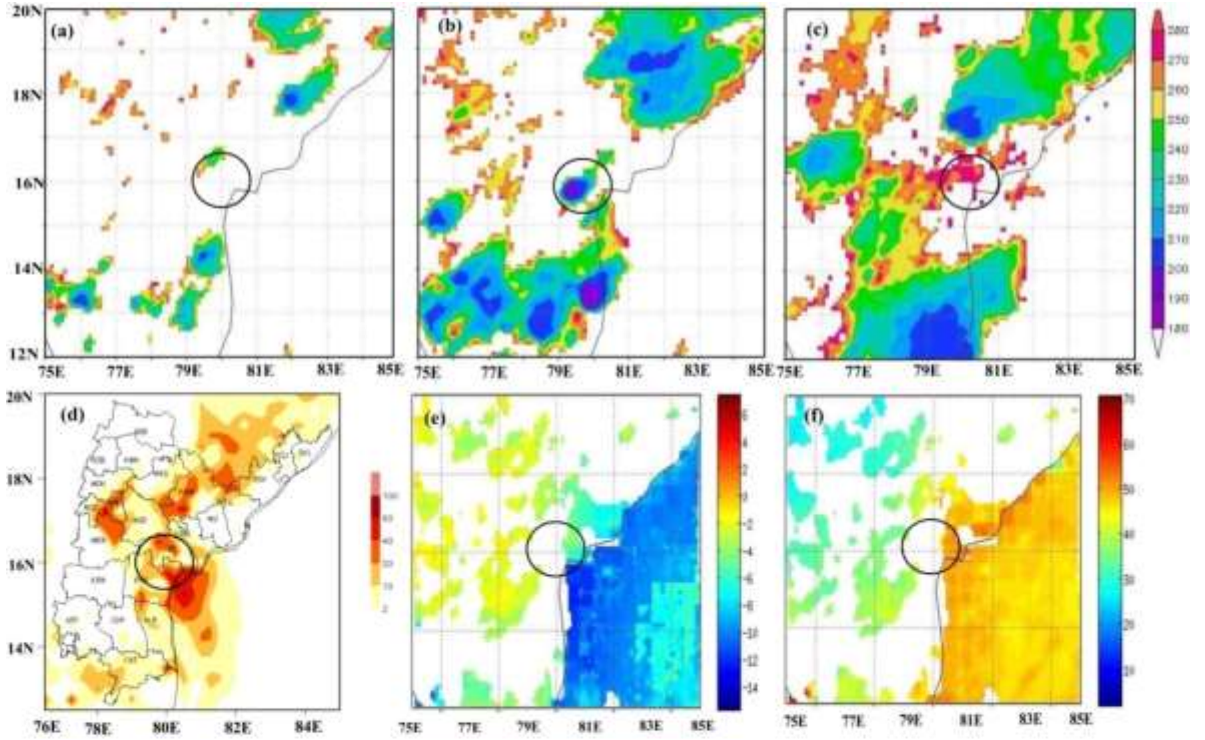

Figure 8: (a)–(c) Spatial distributions of BT (K) (a) before convection, (b) at peak of convection, (c) after convection. (d) – (f) spatial distributions of (d) Rainfall (mm), (e) LI (f) TPW (mm) derived from INSAT-3D Sounder satellite; all for May 9, 2017.

of the MCS and Non-MCS are differentiated (not shown in Figure and Table 4).

Temperature and Humidity profiles derived from MODIS have illustrated the MCS development. The T&Td profiles and Tephigram at Guntur (17.87 N, 82.79E) are shown in Figure . The dew point depression is around 5K at 1000 hPa, which decreased to 4K at 700 hPa and increased to 20K at 400 hPa and then decreased to 5K at 250 hPa. This indicates moist air at lower levels (1000–800 hPa) and dry air above (400 -100 hPa) indicating unstable atmosphere conducive to convection, at these location. From the Tephigram, it is inferred the LCL at 940.12hpa; CCL is 885hpa and the LFC is 840.12 hPa. The difference between LCL and LFC is 100 hPa which is very small and helpful to rapid formation of thunderstorms and MCS within the next 2 hours. The CAPE value is 2666.81J/Kg the CIN value is -44.33 J/Kg indicating favourable for convection (Table 6)

3.4 Case 4 (21 May 2017)

Date	21 May 2017
Area of Event	East Godavari Region
Latitude & Longitude	16.4N ; 80E
Coldest CCT	180 - 208 K
Peak time	1200 UTC

INSAT-3D brightness temperature (BT) data indicates that the BT values have started reducing from 229-243K around 0800 UTC indicating the initial stage for the development of the MCS. Later, the BT values reached 180-215 K at 1200 UTC, indicatng that the MCS

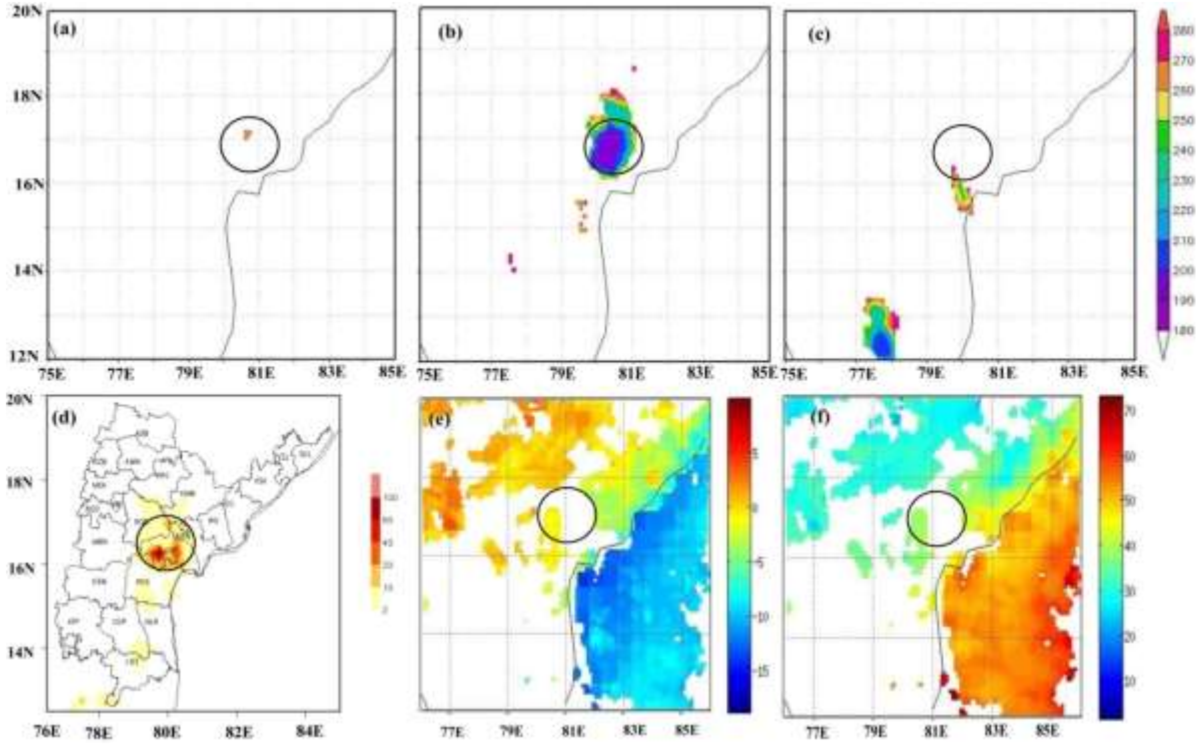

Figure 9: (a)–(c) Spatial distributions of BT (K) (a) before convection, (b) at peak of convection, (c) after convection. (d) – (f) spatial distributions of (d) Rainfall (mm), (e) LI (f) TPW (mm) derived from INSAT-3D Sounder satellite; all for May 21, 2017.

intensified and reached peak stage. Later, the BT started increasing showing the dissipation from 1300 UTC. The MCS completely dissipated by 1700 UTC. When the BT values decrease a threshold, there is a strong development of MCS with intense rainfall (Figure 9).

MODIS Stability Indices of the TERRA pass at 0600 UTC (nearly 6 hours before the peak of MCS) and the AQUA pass for 0900Z (nearly 3 hours before the peak of MCS) are studied. Temperature and Humidity profiles derived from MODIS measurement clearly shows the MCS development. This temperature and Humidity profile at 17.95 N, 79.1 E representative of East Godavari, show that the dew point depression is around 2K at 1000 hPa, which reduced to 0K at 850 hPa and increased to 16K at 400 hPa and again decreased up to 4K at 100 hPa. This indicates the presence of moist air between 1000 – 800 hPa and dry air between 600 - 100 hPa indicating very unstable atmosphere, at the location. From the Tephigram, it is inferred that LCL is 981.34 hPa; CCL is 945 hPa and the LFC is 926.34 hPa. The difference between LCL and LFC is 54 hPa, which is very small and indicates rapid formation of thunderstorms and MCS. The CAPE is 3798.73 J/Kg, CIN is -12.28 J/Kg indicating very high probability of MCS formation (Figure 10, Tables 5 & 6).

3.5 Case 5 (05 May 2017)

INSAT-3D brightness temperature (BT) values are higher than 240 K indicative of no convection over the AP region. INSAT 3D derived LI and TPW values are noted to be > -

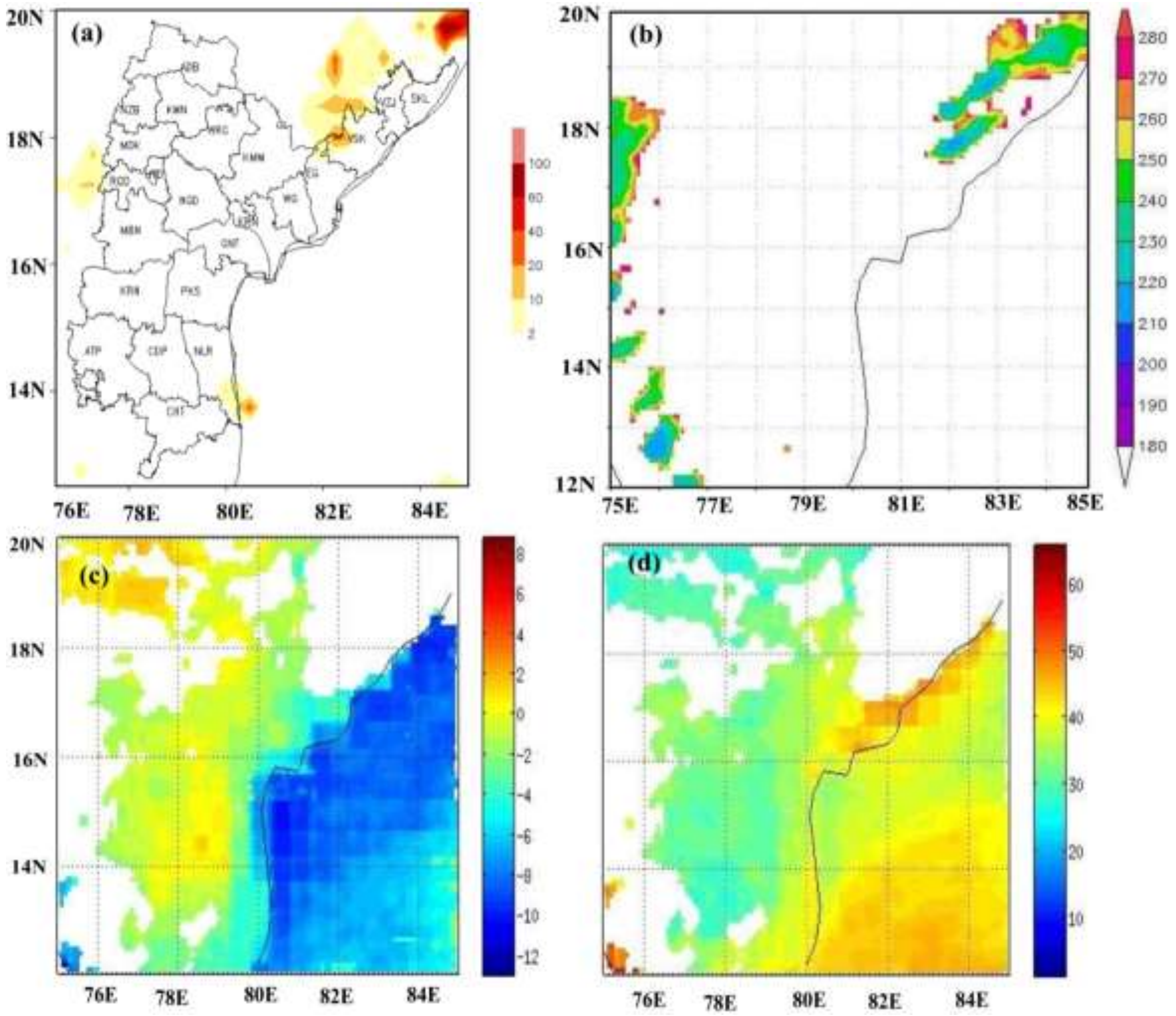

Figure 10: Spatial distributions of (a) Rainfall (mm) (b) BT(K) (c) LI (d) TPW (mm) derived from INSAT-3D Sounder satellite; all for May 5,2017.

2 and < 35 which are indicative of no convection (Figure 10). MODIS based stability Indices computed at one single location of Nellore region (14N; 80E) are given in Table 6. The magnitudes of LI, KI, TPW, TTI, CAPE, CIN and LCL-LFC are indicative of not conducive environment to convection.

3.6 Case 6 (10 May 2017)

INSAT-3D brightness temperature (BT) values are higher than 240 K indicative of no convection over the AP region. INSAT 3D derived LI and TPW values are noted to be > -2 and < 30 which are indicative of no convection (Figure 11).

MODIS based stability Indices computed at one single location of Prakasam (15N; 79E) are given in Table 6. The magnitudes of LI, KI, TPW, TTI, CAPE, CIN and LCL-LFC are indicative of not conducive environment to convection. In both the cases of non-convection, it has been noted that CIN values are negative indicative of favouring convection as representative of atmosphere below the level of free convection, but the small values of CAPE indicate hindering of

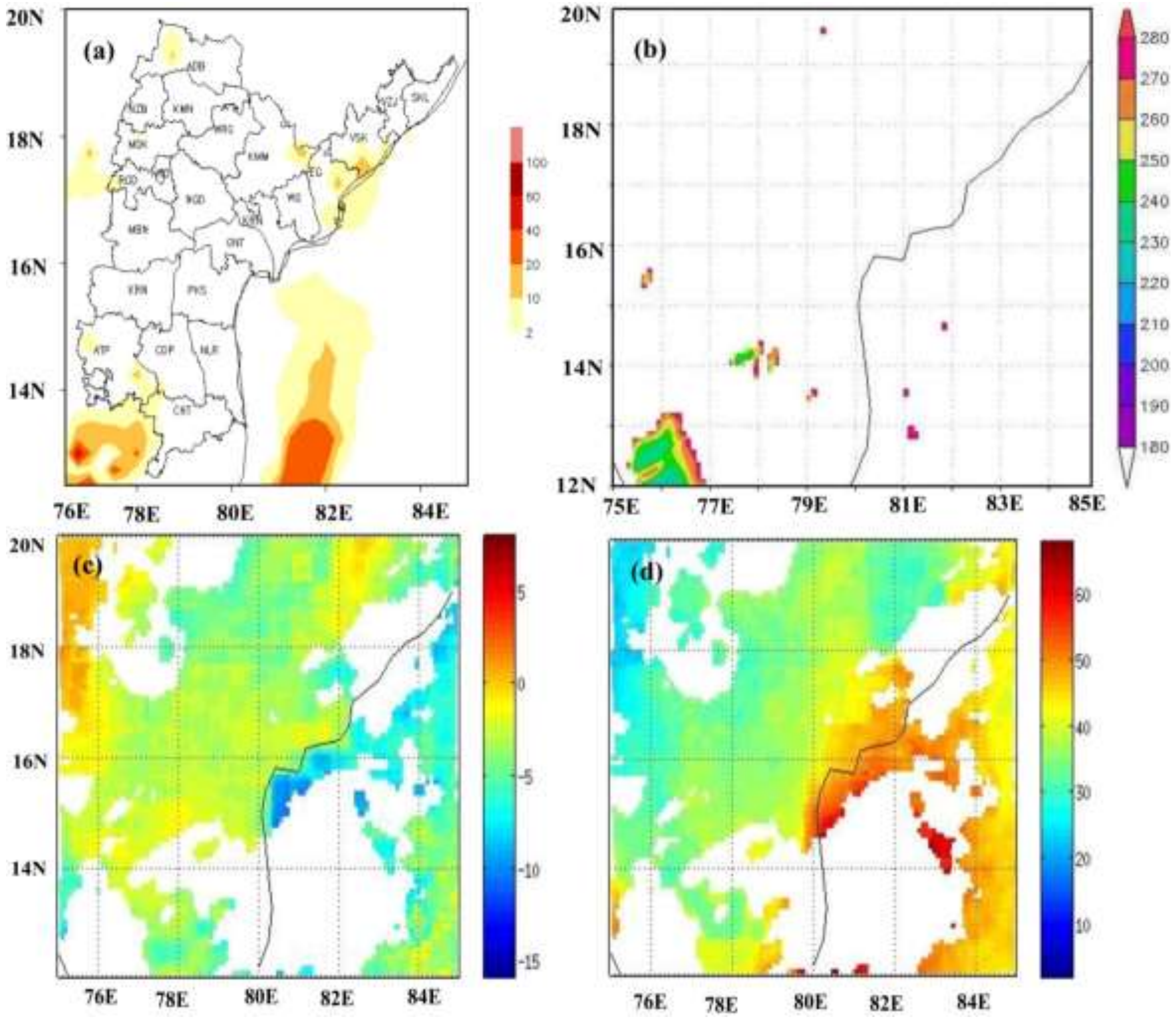

Figure 11: Spatial distributions of (a) Rainfall (mm) (b) BT (K) (c) LI (d) TPW (mm) derived from INSAT-3D Sounder satellite; all for May 10,2017.

convection above the LFC. In summer months due to strong surface heating, near surface may favour convection, but the atmosphere above the boundary layer may not always favour convection and so the convective days are limited.

4. Summary and Conclusions

In this paper, an attempt is made to analyse the thermodynamic variables and stability indices derived from MODIS TERRA and AQUA and INSAT 3D satellites to assess the data products and consequently the predictability of thunderstorms. Andhra Pradesh, a region vulnerable to thunderstorms during the pre-monsoon season, is chosen to be the study area as the results would be helpful to disaster management in Andhra Pradesh. The occurrences of thunderstorms during the current pre-monsoon month of May in 2017 has been investigated.

The gridded daily rainfall data from India Meteorological Department was analysed to identify the rainy days with the assumption that thunderstorm events alone cause rainfall of 2 cm or more during this period. The INSAT 3D images and brightness temperature data at 30 minute interval were used to identify the occurrence and duration of convection. Altogether four thunderstorm events were identified, and in addition two clear sky days were chosen for which the MODIS and INSAT 3D data were collected for analysis. This is done to clearly demarcate the thresholds of different indices representative of atmosphere with convection and non-convection.

(i) All the four cases of convection show the extreme usefulness of INSAT 3D BT data, as an examination of the data at 30 minute interval helped identification of the onset, development and decay of thunderstorm convection. A threshold BT of 190 K for peak convection is clearly identified. The spatial distribution of BT, using 10 km resolution data, helped to delineate the precise area of convection.

(ii) The Lifted Index and the TPW derived using INSAT 3D data have brought out the thresholds related to severe convection. The LI values were less than -5 and TPW > 45 mm are indicative of thunderstorm activity and associated convection. Contrastingly LI values were positive and TPW values were < 34 mm for non-convective cases.

(iii) MODIS data from its two satellites (TERRA and AQUA) have shown that the AQUA data had more relevance to indicate convection due to its timing of passage over the region. Since the thunderstorms under study have occurred during the afternoon, AQUA pass at ~ 3 hours after TERRA had yielded better indicators of stability indices. The 3-hour time interval between the two passes have also brought that the changes in the atmosphere take place within 2-hours period for triggering the convection. This result would be an indicator of lead time of predictability of thunderstorms.

(iv) MODIS based Tephigram had shown the presence of dry air at middle levels over moist air at lower levels indicative of conducive atmosphere for convective activity.

(v) MODIS and INSAT 3Dhas provided more number of stability indices- LI, KI, TTI and TPW and the energy indices- CAPE, CIN, LCL-LFC. As MODIS satellite has only two passes a day, we have to depend more on INSAT-3D products as they are monitored every 30minutes. All of these parameters have yielded excellent results of concurrence between the four thunderstorm events in terms of threshold values. Negative values of LI less than -7; KI >317 K; TTI >50 K; TPW > 52 mm; LCL-LFC: 20-100; CAPE >2000 J/kg and CIN < 44 J/kg significantly indicate strong convection associated with thunderstorm activity.

Contrastingly, the values of LI are > 0.39; KI <293 K; TTI < 40 K; TPW < 32 mm; LCL-LFC >150; CAPE <1386 J/kg and CIN > 57 J/kg which clearly show no convective activity.

The above results demonstrate the usefulness of satellite data to identify and predict convection and thunderstorm activity. The previously identified thresholds for different indices, deduced on physical basis, have proved to be useful. This study reveals the possibilities of increased utilisation of satellite data especially from INSAT 3D for convection studies over India. Since tropical convection is different and the characteristics of convection differ with location and season, there is need for a comprehensive study of the convection over India during different seasons to identify the differences in the characteristics and establish the predictability. Since the ultimate application of a scientific result is to be assessed in terms of societal impact, any advancement in the prediction of thunderstorm activity in terms of lead time, exact location and probable intensity would have enormous use for the public and disaster management. INSAT- 3D-R which is successor to INSAT-3D, gives hourly sounding data of temperature and humidity profiles that will help the study of MCS. This study is an initial attempt and efforts will be made to continue the studies on convective activity over Andhra Pradesh using satellite data.

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