MAUSAM, **69**, 2 (April 2018), 193-208

551.501.8 (548)

Observed structure of convective echoes over southern Indian peninsula during pre-monsoon using TRMM Precipitation Radar

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(*Received 10 July 2017, Accepted 19 March 2018*)

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सार – इस शोधपत्र में उष्णकटिबंधीय वर्षा माप मिशन (TRMM) वर्षा रेडार (PR) के (2A25) डेटा (Z_e) का उपयोग करके दक्षिणी भारतीय प्रायद्वीप (SIP) पर संवहनी प्रतिध्वनि की उर्ध्वाधर संरचना का अध्ययन किया गया है। आपदा मौसम घटनाओं में से प्रचंड धूल भरी आंधी की 25 घटनाओं को भारत मौसम विज्ञान विभाग (आईएमडी) के वार्षिक प्रकाशन के लिए चुना गया है। एक गहन संवहनी प्रतिध्वनि को 4 के एक सेट के रूप में या अधिक सतत संवहनी पिक्सल (क्षेत्र $\geq$ 100 km^2) में परिभाषित किया गया है जो अन्य स्तर पर अधिक 40 dBz या उससे अधिक की परावर्तकता है या किसी स्तर पर अधिक है। 25 बार गुजरने के दौरान TRMM PR द्वारा कुल 492 गहन संवहनी प्रतिध्वनि के सुना गया। SIP पर अधिक, TRMM PR से गहन संवहनी प्रतिध्वनि को 43.3% से बढ़कर 10-15 किमी के बीच देखा गया है। 2 9.3 प्रतिशत 8-10 किलोमीटर के बीच, क्रमशः 8 से कम या बराबर ऊँचाई वाली संवहनी प्रतिध्वनि में 18.1 प्रतिशत, 15 किमी से अधिक ऊंचाई वाले संवहनी प्रतिध्वनि में 9.1%। संवहनी प्रतिध्वनि की तीव्रता के लिए प्रत्यक्ष के रूप से 30 और 40 dBz की ऊंचाई की गणना की गई है। 30 dBz ऊंचाई की आवृत्ति पर 6 और 7 किमी में चोटियों को दिखाता है और 40 dBz की ऊंचाई की आवृत्ति पर 6 किमी पर एकल अधिकतम दिखाता है। 40 dBz ऊंचाई का संचयी आवृत्ति वितरण दर्शाता है कि पूर्व मानसून ऋतु के दौरान के संवहनी प्रतिध्वनि का लगभग 23 प्रतिशत और 7 प्रतिशत 10 किमी की ऊंचाई से अधिक है। 30 और 40 dBz प्रतिध्वनियाँ की औसत ऊंचाई क्रमशः 7.5 और 5.5 किमी पाई गई।

ABSTRACT. Height of convective echoes over southern Indian peninsula (SIP) is studied using Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) measured attenuation corrected radar reflectivity (2A25) data (Z_e). 25 cases of severe thunderstorm events are selected from Disaster Weather Events, an annual publication of India Meteorological Department (IMD). An intense convective echo is defined as a set of 4 or more contiguous convective pixels (area $\geq$ 100 km^2) with Z_e exceeding 40 dBz or more at any level. A total of 492 intense convective echoes are observed by TRMM PR during 25 passes. It is found that 18.1% of convective echoes have height $\leq$ 8 km, 29.3% have height between 8-10 km, 43.3% between 10-15 km and 9.1% of them have height exceeding 15 km in the pre-monsoon season over SIP. Height of 30 and 40 dBz is considered as a proxy for convective intensity. The frequency of 30 dBz height shows peaks at 6 and 7 km while 40 dBz heights show a single maxima at 6 km. The cumulative frequency distribution of 30 and 40 dBz heights show that nearly 23% and 7% of the convective echoes cross 10 km height during pre-monsoon season. The median heights of 30 and 40 dBz echoes were found to be 7.5 and 5.5 km respectively.

Key words – TRMM, Precipitation radar, Intense convective echo.

1. Introduction

North-east India and Kerala witnesses high frequency of more than 40 days of convection during pre-monsoon (March - May) (Tyagi, 2007). The period of maximum heating is April and May and the storms during this period are mesoscale and convective in nature. These convective storms are well known for causing destruction and loss of life and property. However, these are vital in transporting moisture and energy from lower to the upper troposphere (Riehl and Malkus, 1958). A multinational observational and modeling campaign called 'Severe Thunderstorm Observations and Regional Modeling (STORM) program' was initiated by Department of Science and Technology, Government of India in 2005 to improve the understanding of dynamics and thermodynamics of convective storms for refining prediction capabilities over South Asian region (Das *et al*., 2014).

Regional study of convection is important as geographical location controls frequency, type, diurnal

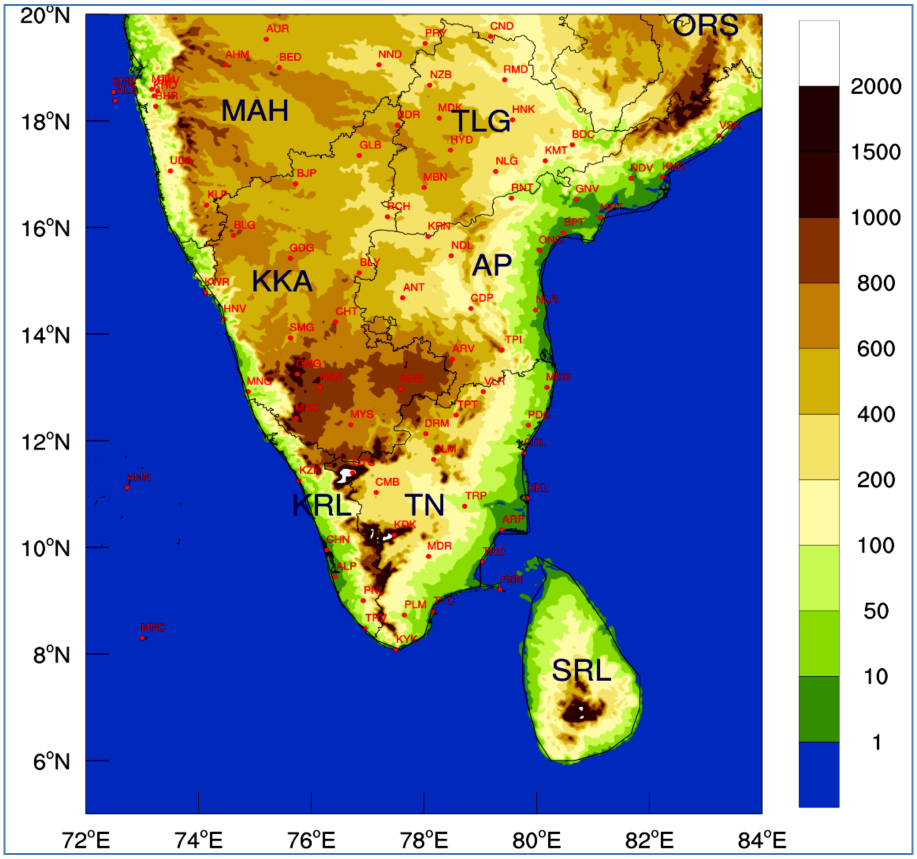


Fig. 1. Topography, height amsl (m) and location of IMD observatories shown in red

nature and the growth of convection. The wind regimes, dynamical and thermodynamical forcings, insolation and moisture advection vary from region to region leading different nature of convection. For example, Houze *et al*. (2007) studied the structure of monsoon clouds over Himalayan region and found that arid western Himalayan region has highest frequency of deep convective cores (DCC). Broad stratiform regions associated with monsoon systems in Bay of Bengal dominate eastern Himalayan region suggesting that terrain has a strong effect on the occurrence of convection. A region can further be sub-divided into smaller sub-regions based on variability in the nature’s convection. Studies on variability of convection over large regions like tropical and subtropical regions over the globe, south Asia, south America, Africa are studied by Houze *et al*. (2015); Romatschke *et al*. (2010); Romatschke and Houze (2010); Zuluaga and Houze (2015). Romatschke *et al*. (2010) have found that location of DCC's changes markedly from India's east coast in pre-monsoon to western Himalayan foothills in the monsoon season.

The motivation of this study on nature of convection for SIP (Fig. 1) comes from the fact that convective activity is severe over this region (Stella and Agnihotri, 2016). Often widespread destruction and loss of life are reported (Balasubramanian and Balachandran, 2008; Suresh, 2012). Topography of this region is unique and extremely complex where the sea meets mountains, plain land and plateau regions coexist. This region primarily comprises of five large Indian States (*viz*., Karnataka (KKA), Kerala (KRL), Tamil Nadu (TN), Andhra Pradesh (AP), Telangana (TLG)) and parts of Maharashtra (MAH), Orissa (ORS) and union territory Goa. The Sayadhri mountains (in MAH and Goa), Malnad region (in KKA) terminating at Nilgiri Hills are located at the borders of three States (TN, KKA and KRL). In western Ghats, highest peak Anamundi has a height 2.6 km is in Iddukki district of KRL. The eastern Ghats run from TN up to ORS through AP. In between these Ghats, plateau has an average elevation of about 0.6 to 0.8 kms. Absence of mesoscale network observation required for observing convection adds to a handicap in improving the understanding and prediction of convection over this region. Human observations of convection are limited in terms of distance. Suresh (2012) has highlighted inherent limitations in storm and hail observations and have shown that frequency of convection using radar is much more

TABLE 1

Details of the cases selected

S. No.	Date	TRMM pass number	Time of TRMM pass (UTC)	Weather	Severity of event	Affected states	Casualties and damages reported
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1.	April 10, 2007	53569	21:13:46.248-22:46:08.881				
2	March 24, 2008	59003	12:43:54.829 - 14:16:18582	Lightning		Trivandrum (Kerala)	2 persons died
	March 13-24, 2008			Heavy Rains		Alappuzha, Ernakulam, Kannur, Kasargode, Kollam, Kottayam, Kozihikode, Malappuram, Palakkad, Pathanamthitta, Thiruvananthapuram, Thrissur and Waynad	16 persons died and 20 injured, One cattle perished; Paddy crops in more than 13000 hectares destroyed; about 400 houses damaged
3.	March 25, 2008	59018	11:49:50.381 - 13:22:14.107	Lightning		Gulbarga and Udupi	3 persons died
	March 21-25, 2008			Heavy Rains		Andhra Pradesh	8 persons died, Cattle perished; Roads, electric motors damaged. Chilli, tobacco, paddy, mango, maize, sunflower etc crops damaged. ; Grapes garden grounded, Several kutcha houses damaged; Loss of about one crore reported to Krishna dam project; power disruption in several areas reported
4.	March 28, 2008	59064	10:30:56.913 - 12:12:20.464	Lightning		Trivandrum (Kerala)	2 persons died and 2 injured
5.	April 2, 2008	59140	07:41:33.767 - 09:13:57.067	Lightning		Vizianagaram (Andhra Pradesh)	2 persons died
	April 1-7, 2008			Lightning		Many districts of Andhra Pradesh	34 persons died and 1643 cattle heads perished
6.	May 8, 2008	59705	13:41:11.377 - 15:13:35.395	Thunder-storm		Wayanad (Kerala)	Extensive damage to agriculture reported and roofs of houses blown away
				Lightning		Dindigul, Salem and Vellore (Tamil Nadu)	Two persons died and 500 livestock died
7.	May 15, 2009	65505	16:46:38.165 - 18:19:01.411				
8.	May 17, 2009	65536	16:30:36.89 - 18:03:00.085				
9.	May 21, 2009	65597	14:26:07.238 - 15:58:30.348				
10.	April 18, 2010	70771	13:33:08.836 - 15:05:32.857	Lightning		Pathanamthitta and Trivandrum (Kerala)	One woman died and twenty injured; Electronic gadgets damaged
11.	April 21, 2010	70817	12:23:29.204 - 13:55:53.090	Lightning		Kolar, Bagalkote, Raichur and Uttara Kannada (Karnataka)	Three persons died
12.	April 24, 2010	70863	11:13:42.818 - 12:46:06.54	Lightning		Kannur, Malapuram (Kerala)	Four persons died and Fourteen injured; Many houses damaged and some plantations uprooted
				Lightning		Thoothkudi (Tamil Nadu)	One person died
13.	April 28, 2010	70924	09:09:42.972 - 10:42:06.532	Lightning		Malapuram, Kottayam and Kozhikode (Kerala)	Five persons died and One injured

TABLE 1(*Contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
14.	April 14, 2011	76394	08:00:45.651 - 09:33:08.647	Lightning		Bangalore Rural, Bellary, Chamrajnagar, Chitradurga, Hassan, Mysore and Ramnagar	Eleven persons died
				Thunder-storm	Severe	Waynad (Kerala),	About 100 Katcha houses partially damaged. Roofs of houses blew away, Some trees/electric poles uprooted disrupting power supply, road traffic and telecommunication services
				Thunder-storm	Moderate	Tirrupur (Tamil Nadu)	Banana plantations and coconut trees damaged
				Lightning		Nagpur (Maharashtra)	One person died
15.	April 23, 2011	76541	18:21:54.923 - 19:54:18.893	Heavy rains		Bangalore and Ramnagara	Four persons died. Some houses damaged. Trees uprooted disrupting to road traffic
16.	April 30, 2011	76648	15:07:59.589 - 16:40:22.852	Lightning		Dharwad and Mandya (Karnataka)	One woman and One boy died
				Heavy rains		Trivandrum (Kerala)	One person died; One house damaged as tree fell over it
17.	March 16, 2013	87338	12:00:01.764 - 13:32:25.819	Lightning		Belgaum (Karnataka)	Two women died and seven injured
18.	May 3, 2013	88086	11:48:01.779 - 13:20:24.696	Lightning		Chickmanglur and Hassan (Karnataka)	Three persons died
	May 3-7, 2013			Heavy Rains		Wayanad (Kerala)	Damage to thousands of banana, mango and rubber plantations reported; Number of villages inundated
19.	May 8, 2013	88162	08:48:55.931 - 10:21:20.062	Lightning		Chitradurga (Karnataka)	One person died; Eight others injured
20.	May 30, 2013	88508	13:35.22.872 - 15:07:45.933	Lightning		Belgaum, Bidar, Dakshin Kannada (Karnataka)	Six persons died and Seven others injured
21.	March 8, 2014	92904	14:46:04.778 - 16:18:28.172	Lightning		Belgaum and Bagalkote (Karnataka)	Two persons died in Badami and Hungund Tehsil while others died in Ramdurg Tehsil
				Hailstorm	Heavy	Bagalkote (Karnataka)	Two persons injured severely in Jamakhandi Tehsil
				Heavy Rains		Coimbatore (Tamil Nadu),	One girl washed away
	March 7-9, 2014			Heavy Rains		Wayanad (Kerala)	One house damaged completely. More than 100 banana plantations uprooted in Athiyoor colony
22.	April 19, 2014	93560	16:54:45.195 - 18:27:08.853	Lightning		Chitradurga, Haveri, Kodagu, Shimoga and Raichur	One man died in Hiriyur Tehsil, other woman in Rannebennur town, One man died in Virajpet Tehsil, One shephard died and one person died in Tirathhalli Tehsil in Manvi Tehsil
				Lightning		Ahemdnagar, Buldana, Hingoli and Satara (Maharashtra)	7 persons died
				Thunder-storm	Moderate	Aurangabad, Buldana and Wasim (Maharashtra)	Damage to standing crops of peanut and amla reported
				Heavy Rains		Buldana, Wasim and Pune (Maharashtra)	About 1000 poultry birds in Pune perished; Damage to corn, amla and peanut reported

TABLE 1(*Contd*.)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	April 16-30, 2014			Heavy Rains		Trivandrum and Wayanad (Kerala)	About 10000 banana plantations in more than 3 acres of land damaged. Jackfruit and Mango trees uprooted; Acres of banana & coconut plantations damaged; About 100 houses completely and 400 partially damaged; About 160 poles and more than 50 trees uprooted causing disruption of traffic and power supply
23.	April 26, 2014	93667	13:40:20.4 - 15:12:44.388	Lightning		Bellary, Bijapur, Bellary and Gadag	5 persons died
24.	April 29, 2014	93713	12:30:30.391 - 14:02:53.871	Lightning		Bellary, Davangere, Dakshin Kannada	5 persons died
				Thunder-storm		Balasore and Bhadrak (Odisha)	2 persons died
25.	June 2, 2014	94247	18:47:53.721 - 20:20:16.909	Lightning		Coimbatore (Tamil Nadu),	3 persons died, Roofs of 100 of houses blown away affecting more than 100 families, Some trees/electric poles uprooted affecting the power supply and traffic
				Squall		Madurai, Namakkal and Toothkudi (Tamil Nadu)	2 persons died including one child due to tree fell upon them while 4 others injured
				Thunder-storm	Severe	Coimbatore (Tamil Nadu)	3 persons died; Roof of several houses blown away affecting more than 100 families; Some trees/electric poles uprooted disrupting power supply & road traffic

than the climatological frequency. SIP has limited radar coverage and intense observational campaigns in the past to study convection in detail are a few. Hence remote sensing is one of the possible techniques to infer the properties of convective systems.

This study focuses on observed characteristics of the pre-monsoon convective echoes over SIP using Tropical Rainfall Measuring Mission (TRMM)'s Precipitation Radar (PR) measured 3-dimensional attenuation corrected radar reflectivity (Z_e). Proxies for the intensity of the storm are wind speed, size of hail, lightning flashes, updraft velocity etc. The context in which each of these terms is used depends on user intent. Many studies implicitly equate the intensity of the storm with updraft velocities. Since this quantity cannot be measured directly, TRMM PR measured Z_e is taken as a proxy for the convective intensity. The vertical extension of Z_e is a strong indicator of the strength of updrafts (Zipser *et al*., 2006). PR has been collecting valuable data especially over the unobserved regions of tropics and sub tropics and this rich dataset is widely used by many. Romatschke and Houze (2011) have shown how nature and size of convective systems contributes to the climatological rainfall of south Asia. Houze *et al*. (2015) and Zipser *et al*. (2006) have shown that nature and frequency of convection varies over oceans and continental regions of low latitude belts. Using PR data, Xu and Zipser (2012); Kumar and Bhat (2016) have shown that land areas have higher fraction of deep and more intense clouds as compared to the oceanic regions. The clouds over land areas are also wider compared to the ocean clouds (Liu *et al*., 2008). Studies focusing on the vertical structures over various parts of the globe are carried out by Kumar and Bhat (2016); Bhat and Kumar (2015); Boccippio *et al*. (2005) etc. The relationship of lightning and reflectivity is studied by Liu *et al*. (2012). The objective of this study is to infer the heights of the intense convective echoes over SIP (Fig. 1) using Z_e. This study will help in improving the understanding about convective echoes over SIP and will help in verifying high resolution model simulations and satellite derived algorithms.

2. Data and methodology

Twenty five (25) numbers of severe convective events over SIP have been selected from 2008 - 2014 (except 2012) from India Meteorological

TABLE 2

Details of the stations whose data is used

S. No. (1)	Station ID (2)	Name (3)	Latitude (°N) (4)	Longitude (°E) (5)	Height (m) (6)	Full Name (7)
1.	43081	NZB	18.67	78.1	381	Nizamabad
2.	43083	MDK	18.05	78.27	472	Medak
3.	43086	RMD	18.77	79.43	156	Ramgundam
4.	43087	HNK	18.02	79.57	269	Hanamkonda
5.	43105	KLN	18.33	84.13	6	Kalingapatanam
6.	43121	GLB	17.35	76.85	458	Gulbarga
7.	43125	BDR	17.92	77.53	664	Bidar
8.	43128	HYD	17.45	78.47	545	Hyderabad(A)
9.	43133	NLG	17.05	79.27	227	Nalgonda
10.	43136	BDC	17.55	80.63	111	Kothagudem (Bhadracha
11.	43137	KMT	17.25	80.15	112	Khammam
12.	43150	VSK	17.72	83.23	66	Visakhapatnam RS/RW
13.	43161	BJP	16.82	75.72	594	Bijapur
14.	43168	MBN	16.75	78	505	Mahbubnagar
15.	43169	RCH	16.2	77.35	400	Raichur
16.	43177	RNT	16.55	79.55	106	Rentachintala
17.	43181	GNV	16.53	80.7	24	Gannavaram
18.	43184	NDV	16.92	81.67	13	Nidadavolu
19.	43185	MPT	16.18	81.13	3	Masulipatnam
20.	43189	KND	16.95	82.23	8	Kakinada
21.	43198	BLG	15.85	74.62	747	Belgaum Samra (A)
22.	43201	GDG	15.42	75.63	650	Gadag
23.	43205	BLY	15.15	76.85	449	Bellary
24.	43212	NDL	15.47	78.48	212	Nandyal
25.	43213	KRN	15.83	78.07	281	Kumool
26.	43220	BPT	15.9	80.47	6	Bapatla
27.	43221	ONG	15.57	80.05	12	Ongole
28.	43225	KWR	14.78	74.13	4	Karwar
29.	43226	HNV	14.28	74.45	26	Honavar
30.	43233	CHT	14.23	76.43	733	Chitradurga
31.	43237	ANT	14.68	77.62	350	Anantapur
32.	43241	CDP	14.48	78.83	130	Cuddapah
33.	43245	NLR	14.45	79.98	20	Nellore
34.	43258	SMG	13.93	75.63	571	Shimoga
35.	43260	CMG	13.25	75.75	1058	Chickmagalur
36.	43263	HSN	13	76.15	960	Hassan
37.	43271	ARV	13.53	78.5	701	Arogyavaram
38.	43275	TPI	13.7	79.38	0	Tirupati (A)
39.	43279	MDS	13	80.18	16	Chennai (Minambakkam)
40.	43284	MNG	12.92	74.88	102	Mangalorel Bajpe (A)
41.	43287	MRC	12.42	75.73	1152	Medikeri (Mercara)
42.	43291	MYS	12.3	76.7	767	Mysore
43.	43295	BNG	12.97	77.58	921	Bangalore

TABLE 2 (*Contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
44.	43301	DRM	12.13	78.03	473	Dharmapuri
45.	43302	TPT	12.48	78.57	390	Tiruppattur
46.	43303	VLR	12.92	79.05	214	Vellore
47.	43311	AMN	11.12	72.73	4	Amini Divi
48.	43314	KZK	11.25	75.78	5	Kozhikode (Calicut)
49.	43317	OTC	11.4	76.73	2249	Uthagamandalam (Oota)
50.	43321	CMB	11.03	77.15	400	Coimbatore (Pilamedu)
51.	43325	SLM	11.65	78.17	278	Salem
52.	43329	CDL	11.77	79.77	12	Cuddalore
53.	43339	KDK	10.23	77.47	2343	Kodaikanal
54.	43344	TRP	10.77	78.72	88	Tiruchchirappalli
55.	43346	KKL	10.92	79.83	7	Karaikal
56.	43348	ARP	10.33	79.38	6	Adiramapatinam
57.	43352	ALP	9.45	76.42	4	Alappuzha(Alleppey)
58.	43353	CHN	9.95	76.27	3	Kochi (Cochin)
59.	43354	PNL	9	76.92	34	Punalur
60.	43360	MDR	9.83	78.08	131	Madurai (A)
61.	43361	TND	9.73	79.03	5	Tondi
62.	43363	PBN	9.21	79.35	11	Pamban
63.	43369	MNC	8.3	73	2	Minicoy
64.	43371	TRV	8.48	76.95	64	Thiruvananthapuram
65.	43376	PLM	8.73	77.65	51	Palayamkottai
66.	43377	KYK	8.08	77.5	37	Kanyakumari
67.	43379	TTC	8.8	78.15	4	Tuticorin
68.	43331	PDC	12.29	79.85	6	Pondicherry

Department (IMD)’s annual publication - Disaster Weather Events. This booklet is compiled on the basis of media and press reports as these have caused widespread damages to the life and property.

TRMM was a highly successful mission between Japan Aerospace Exploration Agency (JAXA) and National Aeronautics and Space Administration (NASA) to monitor rainfall, study latent heat in tropics and subtropics. It was launched in 1997 with 5 sensors onboard (Kummerow *et al*., 1998). TRMM PR is an active microwave sensor (13.8 GHz/2.2 cm), having a swath width of 247 km and scans area between ± 38° N-S, 15-16 times in a day. PR measures the backscattered power by the target which is converted to Z_e (Iguchi *et al*., 2000) (2A25). The 2A25 product of TRMM has high horizontal and vertical resolution of 5 and 0.25 km respectively. Z_e is available at 80 equally spaced levels in the vertical beginning from 0.25 to 20 km. The sensitivity of PR is 17 dBz and cannot detect very small hydrometeors in anvil part of MCS (Li and Schumacher, 2011). TRMM PR also provides rain rate in 80 levels and near surface rain rate, rain type, height of freezing level etc.

TRMM's 2A23 product, called raintype, classifies each rainy pixel detected by PR into convective and stratiform. The raintype classification is based on methods of brightband identification, echo top height and maximum reflectivity in the vertical (Awaka *et al*., 1997). TRMM 3B42 daily gridded rainfall consists of TRMM-adjusted merged-infrared (IR) precipitation and root-mean-square (RMS) precipitation-error estimates. The data is available at 0.25° × 0.25° resolution from ±50° N-S latitudes (Huffman *et al*., 1997).

Lightning Imaging Sensor (LIS) onboard TRMM collects flash rate, location and radiant energy of lightning flashes and this data is available at the website of Global Hydrology Source Center (GHRC, https://ghrc.nsstc.nasa.gov/home) (Chistian *et al*., 1999).

IMD is the national weather agency of India having well distributed network of class-I surface observatories

TABLE 3

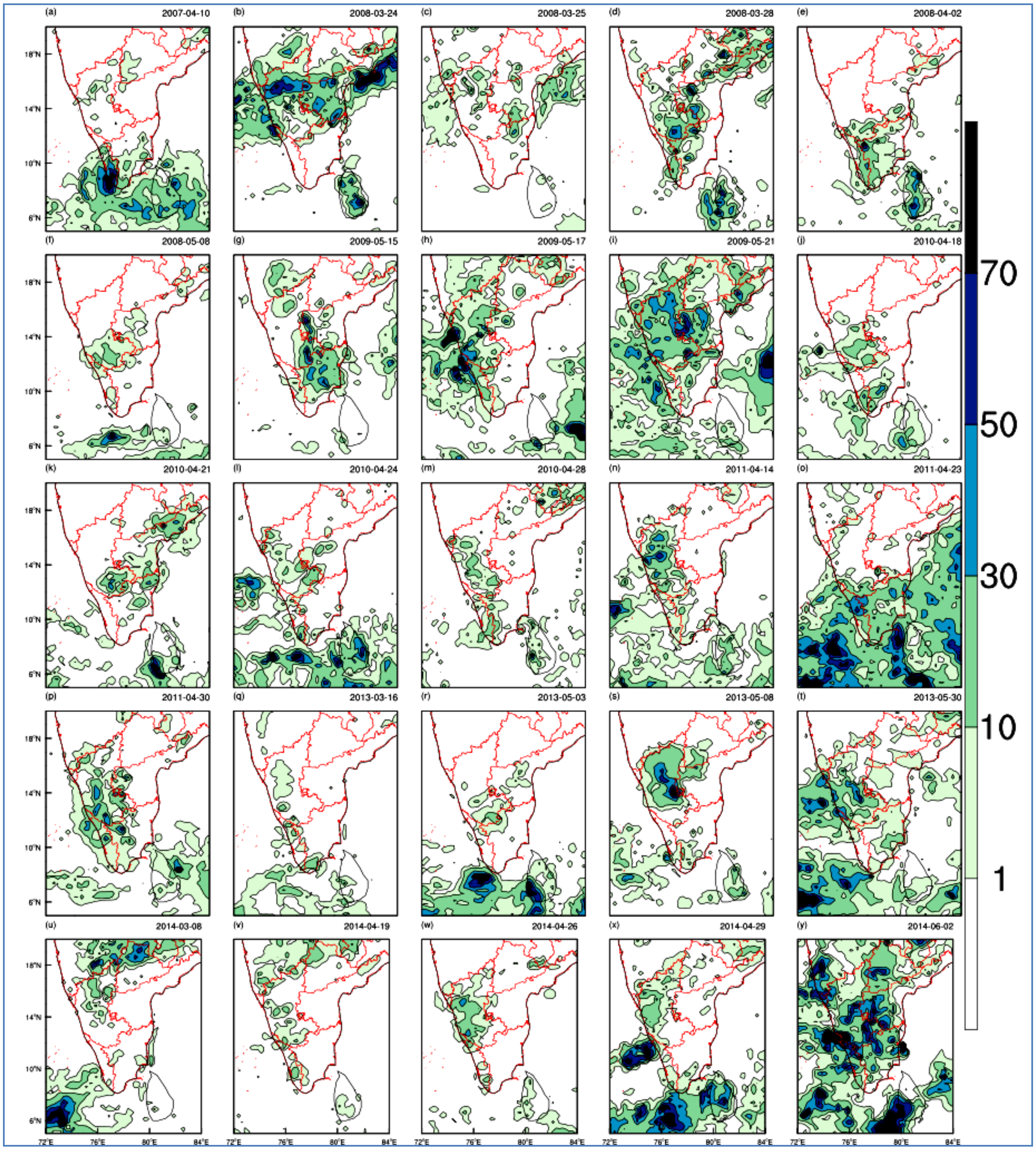
24 hr accumulated rainfall from IMD stations (R is rain, D is drizzle, T is thunder and H is hail)

S. No.	Date	RDT	RT	RD	R	T	DT	D	Others	RDTH
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1.	April 11, 2007	DNA								
2.	March 25, 2008	GDG 78, MDS 56, KWR 27, ARV 12, ONG 9, HNV 7,	MPT 38, KND 16, BPT 13, CHT 4,		NDL 40, BLY 27, MNG, MRC 17, BLG 8, GNV 7, BJP 6, RCH,ANT 5, CMG 2, BDC, NLR 1,					
3.	March 26, 2008	KWR 50, GDG 9, ARV 5	CHT 13	ARP 1	VSK 92, ALP 33, HNV 2	BPT 0			BNG 23, MRC 12, BLY 9	
4.	March 29, 2008	SLM 16, CMB 5, ARV 1	CHN 4	GDG 4	PBN 11, KRN 1		TRV 0		PNL 47, VSK 32, ALP 31, MYS 20, BJP 12, BLY 8, NLG 6, BNG 3, CMG 2, KND 1, BDC 1	
5.	April 3, 2008	BNG 6, TRV 0	CMB 22, CHN 15, KDK 3		PNL 25, ALP 2				SLM 23, MYS 12, MRC 7, HSN 3, KYK 2	
6.	May 9, 2008	CMB 99, ARV 8	KZK 12, CHN 6	ALP 51, SLM 8					MYS 9, MRC 7, HSN 6, MNG 2, CMG 1, BNG 1	
7.	May 16, 2009	BNG 4, KDK 3	MDS 27, CHN 2,CMB 1	ARP 7	TRP 13			TRP 13, KWR 9	BJP 36, MDR 12, KMT 10, VLR 5, KLN 1,MYS 1,	
8.	May 18, 2009	HNV 60,GDG 11, KZK 3	RMD 55, KDK 34, BLG 16, BNG 16, CHT 13, AMN 9, KRN 2			ANT 0	CHN 0		HSN 52, BLY 14, NDL 19, MYS 10, MNG 7, MRC 7, CMG 6, KWR 2	
9.	May 22, 2009	PDC 27, KZK 13, ARV 7, GDG 6	ANT 66, HNV 47, BLG 35, CHT 33, KRN 25, MNC 5	MNG 66, ALP 13, CHN 6, TRV 1	BNG 47, ONG 3, PNL 2				BLY 89, BJP 66, KWR 65, BDC 45, MPT 39, KDK 25, NZB 16, GLB 12, GNV 12, CMG 12, TPI 11, MDK 9, MYS 9, MBN 5, RCH 4, MRC 2, VLR 2, CMB 1, SLM 1, RMD 1	
10.	April 19, 2010	MNG 8	KDK 36, TRV 2						PNL 28, MDR 7, CHT 4, MYS 4, SLM 1, CMG 1	
11.	April 22, 2010		CHT 3						BNG 19, ARV 6, MYS 5, VLR 3, SLM 3, KDK 3	
12.	April 25, 2010		CHT 7, TRV 8					BNG 12	MYS 31, PNL 15, BLG 13, CMG 4, AMN 5	

TABLE 3 (*Contd.*)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
13.	April 29, 2010	GDG 1	TRV 11, KDK 8, BLG 7			CHT 0			PNL 47, MYS 22, CHN 15, MRC 13, KWR 5, HNV 4	
14.	April 15, 2011	KDK 1	BLG 23, GDG 2, CHT 5		AMN 13, PNL 2	TRP 0, ARP 0			MDR 6, MRC 12	MNC 22
15.	April 24, 2011	PDC 46, PBN 29, KZK 19, MDR 10, BLG 1	TRP 11, GDG 6, ARP 3, MDS 2	CDL 21, MNG 4	MNC 31, SLM 31, VLR 12, ALP 1, PNL 7,				BNG 58, MYS 32, KWR 11, MRC 10, TTC 7, TND 5, CDL 4, BJP 1, TRV 1, PLM 1,	
16.	May 1, 2011		TRV 6, BLG 5, CMB 1			ARP 0			MYS 19, GDG 8, BLY 8, MRC 2,	
17.	March 17, 2013				TRV 37, KZK 2, CHN 1				BLG 4, MDR 3, KDK 3	
18.	May 4, 2013	BNG 39		MNC 1	CHN 1	MDR 0			MYS 20, CMG 2, KYK 1	
19.	May 9, 2013	BLG 1	GDG 23		CHT 1			ONG 0, KDK 0	SMG 26, BDR 15, BJP 1	May 9, 2013
20.	May 31, 2013	MNG 45, MNC 39, BNG 31, TRP 31, TND 1	MDR 18, ARP 1	KZK 39, KYK 3, TRV 1			SLM 0		HSN 51, BJP 20, MRC 15, GDG 13, CHT 17, CMG 10, MYS 5	
21.	March 9, 2014		GDG 23		SMG 26, BDR 15,					
22.	April 20, 2014		BLG 3						GLB 8, ALP 7, MYS 4, BDR 3, KDK 2, BJP 1	
23.	April 27, 2014		CHT 3		PNL 20, CHN 3	TRV 0			HSN 13, MRC 13, SMG 8, GLB 5, BLG 2, KWR 2, CMG 2	
24.	April 30, 2014		BLG 3, ARP 1		PNL 20, TRV 16, AMN 5, KYK 3				ALP 39, SMG 10, CMG 8, HNV 4, GDG 3, BDR 2, CHT 2	
25.	Jun 3, 2014		CHT 67, MYS 59, MNC 46, BLG, VLR 45, BNG 28, MRC 24, MDS 22, HNV 1,		KKL 38, CDL 23, KDK 15, SMG 18, BDR, CHN 10, HSN 9, AMN, ARP, TRV 6, PNL, RCH 5, CMB 3, CMG, GLB 2, KZK 1,					

and also collects weather data from part time observatories (PTO). These class-I observatories collect weather data at an interval of 3 hours daily. The rainfall data of the selected stations in SIP was collected from IMD, Pune which archives all the meteorological data after a number of quality checks. In this study, the weather remarks and rainfall from 68 observatories is used (Fig. 1).



Figs. 2(a-y). TRMM 3B42 daily rainfall (mm) on the selected dates

3. Importance of 40 dBz reflectivity and definition of intense convective echo

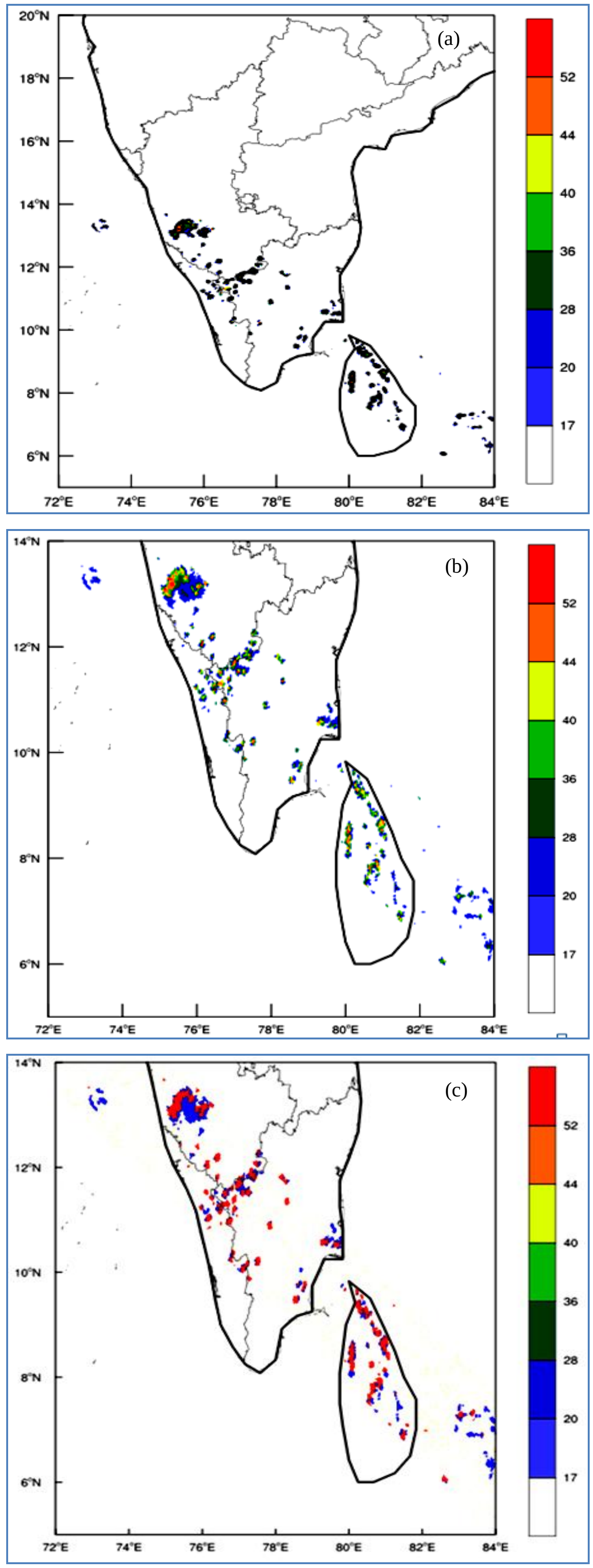
The difference between convective and stratiform precipitation lies in value of vertical velocity. It cannot be measured readily at every point and radar reflectivity is taken as proxy for vertical velocity. Steiner *et al*. (1995) and Awaka *et al*. (1997) have described the methods of differentiating convective from stratiform precipitation based on the formation of brightband, spatial distribution of rain rate and peakedness. A pixel having Z_e of 40 dBz or more is stated to be definitely convective and as per the second criterion, difference between a particular point and background reflectivity should follow a certain criterion.

There are several definitions of convective echo cores in literature. A set of pixels satisfying certain criterion either from single or multiple sensors of TRMM defines a convective echo. Dixon and Weiner (1993) have defined a storm as a region of connected pixels in which Z_e and volume exceeds a threshold of 35 dBz and 50 km^3 respectively. Zipser and Lutz (1994) have used reflectivity values higher than 35 and 40 dBz at 3.9 and 4.4 km height for defining convective clouds over tropical and mid-latitude systems. Nesbitt *et al*. (2000) and Zipser *et al*. (2006) have defined a precipitation feature (PF) consisting of minimum of 4 pixels with a size >75 km^2. Houze *et al*. (2007) have differentiated DCC from a wide convective core (WCC) based on height of 40 dBz Z_e. Zipser *et al*. (2006) and Liu *et al*. (2008) have used thresholds from multiple sensors to define a cloud and PF. This database is used to study regional variations of rainfall by storms having different size, intensity and reflectivity structures. Kumar and Bhat (2016), Bhat and Kumar (2015), Heymsfield *et al*. (2010) have defined cumulonimbus towers (CbT) and intense convective cells (ICCs). CbT's consists of a group of pixels with $Z_e \geq 20$ dBz at 12 km. The ICCs have been constructed by referring to Z_e threshold at 8 and 3 km which are indicative of stage of their development. This study constructs a convective echo core in three steps, firstly by projecting the maxima of Z_e, secondly eliminating the stratiform pixels using TRMM 2A23 algorithm and thirdly grouping a minimum of 4 contiguous convective pixels that have Z_e exceeding 40 dBz at any level. Minimum area of a convective echo is taken to be 100 km^2.

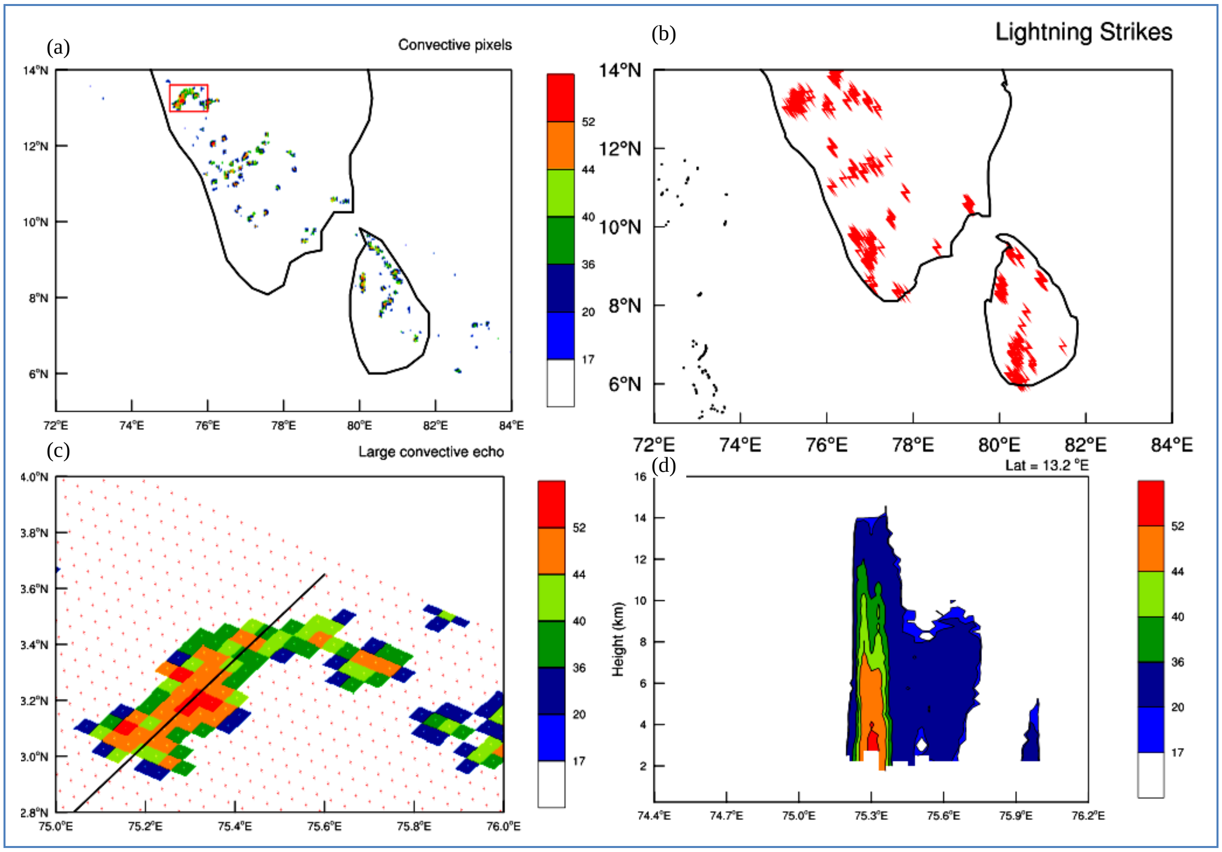
4. Results and discussion

Table 1 has the TRMM pass number, time of the pass, the severity of the event, affected areas, damages and casualties reported on selected days. The thunderstorm and lightning are the most common weather phenomenon affecting a large number of districts in different states of SIP. Table 1 shows that in most of the cases, severe to moderate thunderstorm and/with lightning with heavy rains been reported by media. In case of 2 June, 2014 event, since onset of south west monsoon over Kerala took place 5 days later than the normal onset date of 1 June, hence is considered within pre-monsoon.

A total of 68 synoptic observatories recording 24 hour accumulated rainfall are shown in Fig. 1 (red dots). The details of observatories are given in Table 2. Table 2 contains geographical position, elevation above mean sea level and name of these observatories for reference. Table 3 has the compilation of rainfall and weather information where R is rain, D is drizzle, T is thunder and H is hail. It is to be mentioned here that the synoptic



Figs. 3(a-c). (a) Ze (dBz) at 3 km (b) maximum Ze (dBz) (c) convective and stratiform pixels on 14 April, 2011



Figs. 4(a-d). (a) Convective pixels (b) Lightning strikes (c) Large convective echo (d) vertical cross section of the convective echo on 14 April, 2011

observatories report 24 hour accumulated rainfall at 0300 UTC of the next day. It is important to mention it here that on 17th May, 2009 and 15th April, 2011 Belgaum and Minicoy have reported hail and rainfall of 14 and 22 mm respectively. It indicates the severity of the events in SIP. During 14 - 15 April, 2011 severe thunderstorm and lightning has caused widespread damages to plantations and houses in Waynad, KRL (Table 1). 11 people in 7 districts of KKA have lost their lives due to lightning alone. The corresponding daily precipitation (mm) over entire state of KKA from TRMM 3B42 for this day is shown in Fig. 2n. The island observatory Minicoy has reported hail, thunder, rainfall of 22 mm and drizzle at 0300 UTC of 15th April, 2011. Similarly, Kodaikanal reported 1.3 mm rain and drizzle with thunder. Honnavar, Belgaum, Chikmanglur, Chitradurga, Gadag have reported rainfall and thunder (Table 3). In view of other events accumulated precipitation from TRMM 3B42 is illustrated in Figs. 2(a-y). In view of the spatial distribution of precipitation it is seen that in most of the associated events it is localized (due to brevity, not much discussion is given on precipitation distribution).

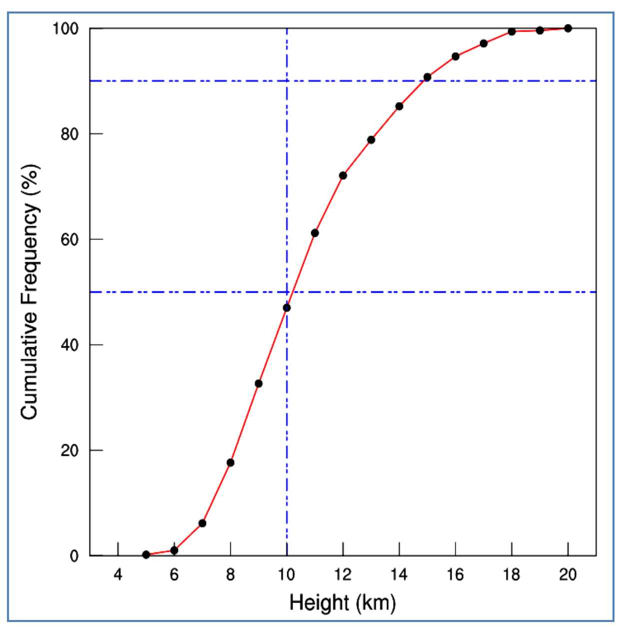


Fig. 5. Cumulative frequency (%) of height (km) of convective echoes

TABLE 4

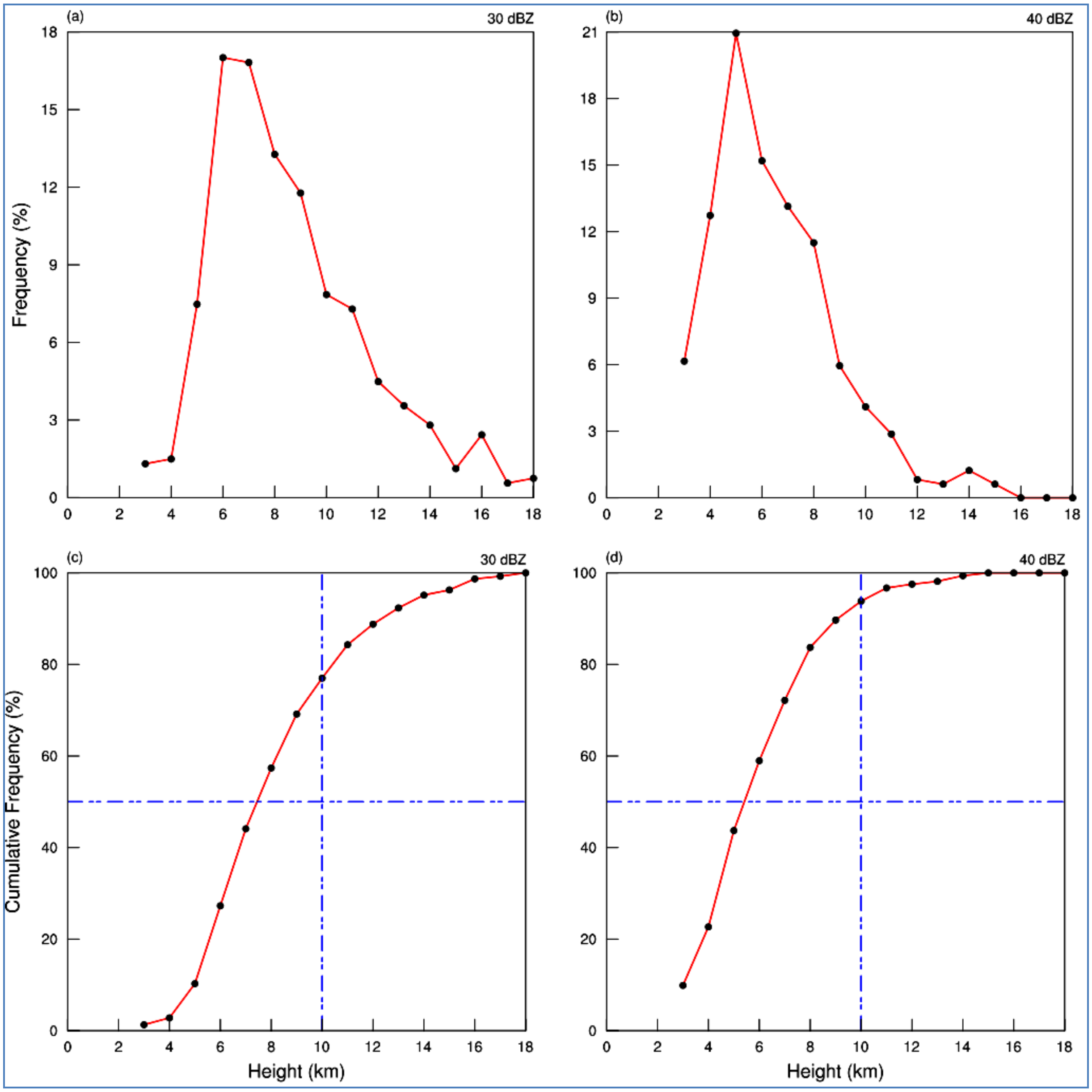
Distribution of heights (km) in each pass

S. No.	Date	Number of convective cells	Below 8 km (≤ 8km)	Between 8-10 km	Between 10-15 km	>15 km	Height of Tallest cloud (km)	Height of Shortest cloud (km)
1.	April 10, 2007	4	3	1	0	0	8.5	7.5
2.	March 24, 2008	25	1	8	14	2	16	6
3.	March 25, 2008	21	6	5	10	0	14.25	5.25
4.	March 28, 2008	31	6	6	17	2	17.5	5.5
5.	April 02, 2008	22	5	4	8	5	18	7
6.	May 08, 2008	18	4	9	4	1	16.75	6.75
7.	May 15, 2009	14	2	5	3	4	16.25	7.75
8.	May 17, 2009	36	12	16	6	2	16.5	6.75
9.	May 21, 2009	30	1	7	13	9	18.25	7.5
10.	April 18, 2010	6	0	2	1	3	19.25	8.25
11.	April 21, 2010	24	1	6	12	5	17.75	8
12.	April 24, 2010	22	2	10	10	0	15	7
13.	April 28, 2010	35	4	14	16	1	15.75	7.5
14.	April 14, 2011	43	6	18	19	0	15	4.75
15.	April 23, 2011	15	8	1	5	1	17.25	6.25
16.	April 30, 2011	8	2	5	1	0	15	7.75
17.	March 16, 2013	13	4	2	7	0	13.75	7.75
18.	May 03, 2013	15	1	3	9	2	19.5	7.25
19.	May0 8, 2013	8	1	0	5	2	17.25	7.25
20.	May 30, 2013	13	2	2	9	0	13	7.75
21.	March 8, 2014	25	8	6	11	0	13.5	6.25
22.	April 19, 2014	5	1	2	2	0	14.25	8
23.	April 26, 2014	9	0	1	7	1	17	10
24.	April 29, 2014	23	4	7	12	0	13.75	7
25.	June 02, 2014	27	5	4	12	6	17.5	6.25
		492	89 (18.1%)	144 (29.3%)	213 (43.3%)	46 (9.3%)		

4.1. *TRMM PR observations*

Fig. 3(a) shows reflectivity at 3 km on 14 April 2011. It illustrates a number of small and large echoes with reflectivity ranging from 17 to 52 dBz during TRMM pass. Fig. 3(b) is the projection of maximum reflectivity within the 80 vertical levels. The largest echo is seen over KKA and smaller over KRL, TN and SRL. Swath of TRMM PR shows convective and stratiform regions in red and blue colors respectively [Fig. 3(c)]. It is seen that convective and stratiform regions co-exist within the same echo.

Fig. 4(a) illustrates convective pixels only (and not stratiform pixels) showing that these can either be a single pixel or comprise of contiguous pixels forming a convective echo. A variety of shapes and sizes of convective echoes are seen by TRMM. The widest convective echo is bounded by the red box comprising of 92 convective pixels [Fig. 4(a)]. Corresponding lightning data from TRMM LIS is shown in Fig. 4(b). It depicts the lightning flashes associated with the convective echoes. The non-missing and missing data in the TRMM PR swath are shown by white and red dots respectively in Fig. 4(c). The reflectivity of this echo is more than 52 dBz



Figs. 6(a-d). Frequency and cumulative frequency (%) of heights (km) of 30 and 40 dBz echoes

[Fig. 4(c)], at the centre and corresponding vertical cross section along the line of maximum Ze is shown in Fig. 4(d). Fig. 4(d) shows the profile of Z_e of this widest convective echo. It shows that its convective core is 60 km wide with depth exceeding 14 km. This core is vertically erect and maximum Z_e is distributed in the lower levels.

4.2. *Distribution of convective echo top height*

The echo top height is defined as the height of ≥17 dBz. The tallest pixel forming the convective echo is taken as the height of the echo. The distribution of top heights in different TRMM passes during pre-monsoon is shown in Table 4. A total of 492 convective echoes are observed by TRMM PR during 25 passes and maximum of them (43.3%) are very deep and lie within the range of 10-15 km followed by 29.3% lying within the range of 8-10 km respectively. 18.1% and 9.1% lie within the range of ≤ 8 and >15 km respectively. The tallest convective echo top was observed on 3 May 2013 having a height of 19.5 km. The smallest was observed on 14th April, 2011 with a height of 4.75 km. The cumulative frequency distribution of the height of the intense convective echoes is shown in Fig. 5. This shows that 48% of the echoes cross 10 km height and 10% of them have height above 15 km. Das *et al*. (2015) have reported that cloud tops over Bangladesh reach as high as 18-20 km in cases of severe storms.

4.3. *Distribution of height of 30 and 40 dBz echoes*

Height of 40 dBz echo is taken as proxy for the convective intensity (Zipser *et al*., 2006; Cecil *et al*., 2005; Kumar and Bhat, 2016). Higher the height attained by 40 dBz in a convective echo, more intense it is. Figs. 6(a&d) shows frequency and cumulative frequency distribution of 30 and 40 dBz heights. Frequency of 30 dBz shows peak at 6 and 7 km while frequency of 40 dBz shows single maxima at 6 km respectively [Fig. 6(a&b)]. The cumulative frequency distribution of 30 and 40 dBz [Fig. 6(c&d)] shows that nearly 23% and 7% of the convective echoes cross 10 km height. The median heights of 30 and 40 dBz echoes were found to be 7.5 and 5.5 km respectively.

5. Conclusions

Vertical structure of the convective echoes over SIP are studied using TRMM PR 2A25 data. 25 cases of severe thunderstorm events are selected from Disaster Weather Events, an annual publication of India Meteorological Department. A convective echo is defined as a set of 4 or more contiguous convective pixels (size $\geq$ 100 km^2) that have reflectivity exceeding 40 dBz or more at any level. A total of 492 convective echoes are observed by TRMM PR during 25 passes. Maximum convective echoes over south peninsula (43.3%) are very deep and extend between 10-15 km range in vertical followed by 29.3% lying in the range of 8-10 km respectively. 18.1% and 9.1% of the echoes have height of $\leq$ 8 and >15 km respectively. Frequency of 30 dBz shows peak at 6 and 7 km while frequency of 40 dBz shows single maxima at 6 km. The cumulative frequency distribution of 30 and 40 dBz show that nearly 23% and 7% of the convective echoes cross 10 km height over this region in pre-monsoon season. The median heights of 30 and 40 dBz echoes were found to be 7.5 and 5.5 km respectively.

Acknowledgements

The authors gratefully acknowledge TRMM measured reflectivity available freely on web. The first author acknowledges the help rendered by Ms. Mary Haley and Shri Dennis Shea of UCAR. The authors are thankful to Dr. S. B. Thampi, DDGM, RMC Chennai for his constant encouragement and support to take up this study. The authors are also thankful to the reviewer for improving this manuscript.

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