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

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ABSTRACT. Height of convective echoes over southern Indian peninsula (SIP) is studied using Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) measured attenuation corrected corrected radar reflectivity (Z_r). 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 ≥ 100 km^2) with Z_r 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 ≤ 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 maximum 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
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 subdivided 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

![Fig. 1. Topography, height amsl (m) and location of IMD observatories shown in red](image-url)
### 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      | April 10, 2007| 53569            | 21:13:46.248 - 22:46:08.881 | Lightning   | Trivandrum (Kerala) | 2 persons died                                                                 | 16 persons died and 20 injured, One cattle perished; Paddy crops in more than 13000 hectares destroyed; about 400 houses damaged |
|        | March 24, 2008| 59003            | 12:43:54.829 - 14:16:18.82  | Heavy Rains | Alappuzha, Ernakulam, Kannur, Kasargode, Kollam, Kottayam, Kozhikode, Malappuram, Palakkad, Pathanamthitta, Thiruvananthapuram, Thrissur and Waynad | 2 persons died                                                                 | 16 persons died and 20 injured, One cattle perished; Paddy crops in more than 13000 hectares destroyed; about 400 houses damaged |
|        | March 13-24, 2008| 59018          | 11:49:50.381 - 13:22:14.107 | Lightning   | Guilbarga and Udupi | 3 persons died                                                                 | 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 |
|        | March 25, 2008| 59064            | 10:30:56.913 - 12:12:20.464 | Lightning   | Trivandrum (Kerala) | 2 persons died and 2 injured                                                   | 2 persons died and 2 injured                       |
| 2      | March 21-25, 2008| 59705          | 13:41:11.377 - 15:13:35.395 | Thunderstorm | Wayanad (Kerala)     | Extensive damage to agriculture reported and roofs of houses blown away | 34 persons died and 1643 cattle heads perished |
| 3      | April 2, 2008  | 59771            | 13:33:08.836 - 15:05:32.857 | Lightning   | Pathanamthitta and Trivandrum (Kerala) | One woman died and twenty injured; Electronic gadgets damaged | Four persons died and Fourteen injured; Many houses damaged and some plantations uprooted | One person died |
| 4      | April 18, 2010 | 70024            | 09:09:42.972 - 10:42:06.532 | Lightning   | Malappuram, Kottayam and Kozhikode (Kerala) | Five persons died and One injured | One person died |
| Date            | Code  | Time Range         | Event Type | Location | Details                                                                                                                                                                                                 |
|-----------------|-------|--------------------|------------|----------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| April 14, 2011  | 76394 | 08:00:45.651 - 09:33:08.647 | Lightning  | Bangalore Rural, Bellary, Chamrajnagar, Chitradurga, Hassan, Mysore and Ramnagar, 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 | Eleven persons died                                                                                                                                 |
| April 14, 2011  | 76394 | 08:00:45.651 - 09:33:08.647 | Thunderstorm | Moderate | Tirupur (Tamil Nadu), Nagpur (Maharashtra), Banana plantations and coconut trees damaged, One person died                                                                                                   |
| April 14, 2011  | 76394 | 08:00:45.651 - 09:33:08.647 |           | Light    | Bangalore and Ramnagar, Four persons died. Some houses damaged. Trees uprooted disrupting to road traffic                                                                                             |
| April 14, 2011  | 76394 | 08:00:45.651 - 09:33:08.647 |           | Thunderstorm | Dharwad and Mandya (Karnataka), Three persons died, One woman and One boy died                                                                                                                         |
| April 14, 2011  | 76394 | 08:00:45.651 - 09:33:08.647 |           | Heavy Rains | Belgaum (Karnataka), Two women died and seven injured                                                                                                                                             |
| April 14, 2011  | 76394 | 08:00:45.651 - 09:33:08.647 |           | Lightning | Chickmaglur and Hassan (Karnataka), Wayanad (Kerala), Three persons died, Damage to thousands of banana, mango and rubber plantations reported; Number of villages inundated |
| March 8, 2013   | 88162 | 08:48:55.931 - 10:21:20.062 | Lightning  | Chitradurga (Karnataka), Nine persons died, Eight others injured                                                                                                                             |
| May 3, 2013     | 88508 | 08:48:55.931 - 10:21:20.062 | Lightning  | Belgaum, Bidar, Dakshin Kannada (Karnataka), Six persons died and Seven others injured                                                                                                             |
| 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, Two persons injured severely in Jamakhandi Tehsil, One girl washed away |
| March 8, 2014   | 92904 | 14:46:04.778 - 16:18:28.172 | Hailstorm  | Bagalkote (Karnataka), Coimbatore (Tamil Nadu), Wayanad (Kerala), One house damaged completely. More than 100 banana plantations uprooted in Athiyoor colony |
| March 8, 2014   | 92904 | 14:46:04.778 - 16:18:28.172 |           | Heavy Rains | Belgaum and Bagalkote (Karnataka), Two persons died in Badami and Hungund Tehsil while others died in Ramdurg Tehsil, Two persons injured severely in Jamakhandi Tehsil, One girl washed away |
| March 8, 2014   | 92904 | 14:46:04.778 - 16:18:28.172 |           | Heavy Rains | Belgaum and Bagalkote (Karnataka), Two persons died in Badami and Hungund Tehsil while others died in Ramdurg Tehsil, Two persons injured severely in Jamakhandi Tehsil, One girl washed away |
| March 8, 2014   | 92904 | 14:46:04.778 - 16:18:28.172 |           | Heavy Rains | Belgaum and Bagalkote (Karnataka), Two persons died in Badami and Hungund Tehsil while others died in Ramdurg Tehsil, Two persons injured severely in Jamakhandi Tehsil, One girl washed away |
| April 19, 2014  | 93560 | 16:54:45.195 - 18:27:08.853 | Lightning  | Chitradurga, Haveri, Kodagu, Shimoga and Raichur, About 1000 poultry birds in Pune perished; Damage to corn, amla and peanut reported, One man died in Hiriyur Tehsil, other woman in Rannebe).__nur town, One man died in Virajpet Tehsil, One shephard died and one person died in Tirathhalli Tehsil in Manvi Tehsil, 7 persons died |
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 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

| (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 |
| 25. | June 2, 2014 | 94247 | 18:47:53.721 - 20:20:16.909 | Lightning | Madurai, Namakkal and Toothkudi (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 | Coimbatore (Tamil Nadu), | 2 persons died including one child due to tree fell upon them while 4 others injured |
| | | | | Thunderstorm | 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 |

TABLE 1(Contd.)
TABLE 2

Details of the stations whose data is used

| S. No. | Station ID | Name | Latitude (°N) | Longitude (°E) | Height (m) | Full Name |
|--------|------------|------|---------------|---------------|------------|-----------|
| 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        | Rangunmad  |
| 4.     | 43087      | HNK  | 18.02         | 79.57         | 269        | Hanamkonda  |
| 5.     | 43105      | KLN  | 18.33         | 84.13         | 6          | Kalingapatnam |
| 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(Bhadrach) |
| 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        | Belgam 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        | Chitravurma |
| 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 | Tirupattur |
| 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 | 2433 | Kodaikanal |
| 54. | 43344 | TRP | 10.77 | 78.72 | 88 | Tiruchirappalli |
| 55. | 43346 | KKL | 10.92 | 79.83 | 7 | Karaikal |
| 56. | 43348 | ARP | 10.33 | 79.38 | 6 | Adirampatinam |
| 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      | 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, CMB 15, KDK 3 | 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, KL 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, BJ 66, KWR 65, BDC 45, MPT 39, KDK 25, NZB 16, GLB 12, GNV 12, CMG 12, TPL 11, MDK 9, MYS 9, MBN 3, 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.)

|   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|
| 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 | CHN 1 | MDR 0 |
| 18. | May 4, 2013 | BNG 39 | MNC 1 | CHN 1 | MDR 0 |
| 19. | May 9, 2013 | BLG 1 | 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 |
| 20. | May 31, 2013 | GDG 23 | CHT 1 | ONG 0, KDK 0 | SMG 26, BDR 15, BJP 1 |
| 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, MNG, 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).
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
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, Chikmanalur, 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).
Table 4
Distribution of heights (km) in each pass

| S. No. | Date       | Number of convective cells | Below 8 km (≤ 8 km) | 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 3, 2013    | 15                          | 1 3                  | 9 2             | 19.5 7.25        |        |                             |                             |
| 19.    | May 9, 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.
Fig. 4(c)], at the centre and corresponding vertical cross section along the line of maximum $Z_e$ 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 $\geq 17$ 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 $\leq 8$ 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 ≥ 100 km²) 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 ≤ 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.

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