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Case Study

Heavy rainfall and thunderstorms in south interior Karnataka: a case study on august 31, 2023

Chanabasanagouda S. Patil[1,2] · **Darga Saheb Shaik**[1] · **Kamsali Nagaraja**[2]

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Abstract
Study aims to conduct a synoptic and thermodynamic analysis of significant rainfall events that happened during the break monsoon season. During the investigation of meteorological events, it was observed that the monsoon trough at mean sea level passed along the foothills of the Himalaya. On August 31, 2023, there was a cyclonic circulation observed in the northeast Bay of Bengal as well as adjacent areas, reaching an altitude of 5.8 km above mean sea level (AMSL). This circulation tilted southwestward with height. During the period of August 31-September 2, 2023, there was a cyclonic circulation persistent that occurred inside a particular geographical area. This phenomenon extended up to a height of 4.5 km AMSL and exhibited a south-westward tilt as the altitude increased. On August 31, 2023, the Convective Available Potential Energy (CAPE) was measured to be 2153 J/kg, whereas the Convective Inhibition Energy (CINE) was recorded as 0 J/kg. INSAT-3D satellite image showed a cloud top temperature of – 40 °C to – 60 °C. The Doppler Weather Radar (DWR) pictures also showed convective clouds to support this phenomenon. The synoptic and thermodynamic indices indicate a high likelihood of significant precipitation occurring over Bengaluru and its surrounding regions.

Article Highlights

- South interior Karnataka experienced wide-spread rainfall with isolated heavy to very heavy rainfall during south-west monsoon on 31 August 2023.
- Cyclonic circulation was extended up to 4.5 km AMSL with CAPE value of 2153 J/kg.
- The synoptic and thermodynamic indices showed a likelihood of the significant precipitation occurrence over Bengaluru and its surrounding regions during this event.

Keywords Heavy rainfall · Synoptic situations · Thermodynamic indices

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✉ Darga Saheb Shaik, sk.darga@gmail.com | [1]India Meteorological Department, Bengaluru 560001, India. [2]Department of Physics, Bangalore University, Bengaluru 560056, India.

1 Introduction

Thunderstorm is a natural occurrence phenomenon characterized by the presence of thunder and lightning, often accompanied by rainfall, strong winds, and sometimes, even strong squall. Strong thunderstorms can cause the flash floods and trigger landslides, lightning-induced wildfires, tornadoes, wind, hail, and other hazards that can endanger people's lives and property as well as have an adverse sociological and economic impact in local scale [1–6]. The metropolitan areas' cities are confronted with significant obstacles, such as infrastructural constraints and traffic congestion, which pose challenges to decision makers [7]. Hence, it is imperative to give advance warning about an approaching thunderstorm in order to minimize the extent of harm inflicted on individuals and their belongings at a local level. In India, thunderstorms typically occur during the summer season in areas characterized by high levels of humidity and the convergence of vertical air masses. However, it is important to note that during the monsoon season, a decrease in surface temperature is counterbalanced by the presence of enough moisture in the deeper layers of the troposphere. As a result, the country continues to experience thunderstorm and precipitation during monsoon season. According to Manohar [8], a study was conducted on thunderstorm activity, revealing that during the mid-monsoon season in July and August, there is a relatively low occurrence of thunderstorms across the entire nation. However, in the months of June and September, which mark the onset and withdrawal phases of the monsoon season, the activity of thunderstorms is more prominent. The presence of instability plays a significant role in the formation and development of thunderstorms. Thermodynamic indicators have proven to be useful tools in forecasting and predicting the occurrence of thunderstorms [9]. Prediction of thunderstorms using stability indices have been widely attempted by many Indian researchers [10–13]. For example, Duraisamy et al. [10] investigated different atmospheric stability indices in relation to the occurrence of thunderstorms over Delhi region during pre-monsoon season for the years 1999–2004 and found the critical values of thermodynamic indices are matched well with the thunderstorm day's values over Delhi region. Basu and Mondal [14] attempted to find out suitable thermodynamic indices for forecasting thundersqualls over Kolkata during pre-monsoon seasons. Mukhopadhyay et al. [15] suggested an objective method using stability indices for occurrence of the thunderstorm and non-thunderstorm days at three locations over north east India. Khole and Biswas [16] studied role of total total stability index in forecasting of thunderstorms over Kolkata, India. Further, Agnihotri [17] evaluated the stability indices with specific thresholds in relation to forecasting thundery and non-thundery days over Bengaluru during pre-monsoon season.

Cloud imaging and atmospheric soundings collected by geostationary and polar orbiting satellites have been used since 2013. The cloud images produced by the INSAT 3D at 30-min intervals are used to examine the evolution of clouds from cumulus to synoptic scale. The imageries serve a purpose for capturing mesoscale convective clouds. Bhatia and Kalsi [18] reported the development of convective clouds in a weekly triggered environment using imagery. Yavuz et al. [9] predicted for nowcasting the thunderstorm accompanied by rain showers at Istanbul Ataturk International Airport by using radar and lightning images. Gupta et al. [11] reported the temporal and spatial variation of thunderstorm activity can captured by DWR images with high degree of accuracy. The assimilation of DWR observations along with stability indices have acquired a greater skill and are playing increasingly important role in mesoscale weather prediction [9, 19]. When attempting to estimate the likelihood of thunderstorms, meteorologists analyze synoptic aspects as well as thermodynamic indices. Present study is being followed by the Peppier [20] who conducted a study on stability indicators. Further, the indices solely serve to indicate the likely occurrence of thunderstorms, the systematic approaches were developed by Gordon and Albert [21] as well as Miller [22]. It is possible to recover vertical velocity, relative humidity, and wind shear from the result of a numerical weather prediction model (NWP), and these three variables are extremely helpful when attempting to diagnose the structure of a thunderstorm. During the monsoon season, Unashish et al. [23] studied thunderstorm indices in order to comprehend thunderstorms.

An attempt has been made in this study to comprehend the synoptic features and thermodynamic indices that were present during an event of severe thunderstorm; it was accompanied by substantial rainfall that occurred on 31 August 2023. Synaptic and thermodynamic indexes indicate a high likelihood of heavy rain over Bengaluru. The application of a systematic study to assess atmospheric conditions proves highly beneficial for meteorologists in their forecasting of thunderstorms and associated parameters.

2 Description of the event

Bengaluru is located on the Deccan plateau of India. The city of Bengaluru has seen its population rise steadily throughout the years. On August 31, 2023, Bengaluru and its surrounding areas received a total of 90 mm of precipitation. This rainfall was noted within a 100 km radius and was reported by 11 meteorological stations. The amount of rainfall recorded ranged from 60 to 110 mm. Additionally, there was extensive rainfall in the south interior Karnataka region due to the active monsoon. The active monsoon is characterized by precipitation that exceeds the usual amount by a factor of 1.5 to 4, with widespread and fairly uniform distribution. If the sub-division is situated on the west coast, the minimum rainfall at two stations should be 50 mm. However, if it is located elsewhere, the minimum rainfall should be 30 mm [24].

3 Data and methodology

The thunderstorm activity and meteorological data i.e., hourly observations of wind speed, temperature, cloud cover, and DWR images for the event on August 31, 2023 were collected from the India Meteorological Department (IMD), Bengaluru.

This study employs the ECMWF-ERA5 reanalysis charts, specifically the surface chart and wind analysis for different pressure levels, to better understand the synoptic characteristics. The thermodynamic indices and Te-Phi gram were obtained from the Department of Atmospheric Science at the University of Wyoming through http://weather.uywo.edu/upperair/sounding.html.

To anticipate thunderstorms, a number of indices have been developed based on thermodynamic properties. Thermodynamic indices were calculated utilizing the vertical distribution of temperature and humidity using radio sonde data [13, 15, 25, 26]. The Atmospheric stability parameters and indices such as CAPE, CINE, Bulk Richardson Number (BRN), Showalter Index (SI), Lifted Index (LI), Total Total Index (TTI), Severe Weather Index (SWEAT), and K Index (KI) were calculated as follows:

$$CAPE = \int_{LFC}^{LNB} R_d\left(T_{vc} - T_{ve}\right) dLnP \tag{1}$$

Here 'LFC' is the level of free convection, 'LNB' is the neutral buoyancy, 'R_d' is the gas constant, 'T_{vc}' is the virtual is the virtual temperature of the cloud parcels lifted from a specified level, 'T_{ve}' temperature of the environment, and 'P' is pressure.

$$CINE = \int_{P_i}^{P_f} R_d\left(T_{vp} - T_{ve}\right) dLnP \tag{2}$$

Here 'P_i' is the pressure at the atmospheric level where the parcel originates, 'P_f' is the pressure at the LFC, 'R_d' is the gas constant; 'T_{vp}' is the virtual temperature of the lifted parcel, 'T_{ve}' is the virtual temperature of the environment, and 'P' is pressure.

$$BRN = \frac{\left(\frac{g}{T_v}\right)\Delta\theta_v\Delta_z}{(\Delta U)^2 + (\Delta V)^2} \tag{3}$$

Here 'g' is the gravitational acceleration, 'T_v' is the virtual temperature, 'Δ_z' is the layer of thickness, '$\Delta\Theta_v$' is the difference across a 'Δ_z' & 'ΔU', and 'ΔV' are the horizontal wind component changes across the same layer.

$$SI = T_{500} - T_{P500} \tag{4}$$

Here T_{500} is the temperature of 500 hPa level and T_{P500} is the temperature of a parcel that lifted dry adiabatically to the its condensation level from 850 hPa and then moist adiabatically to 500 hPa.

$$LI = T_{500} - T_{P_{500}} \tag{5}$$

Here, 'T500' is the environmental temperature at 500 hPa and 'T_{P500}' is the parcel temperature, it is lifted with adiabatically from 500 m above the surface.

$$TTI = T_{850hPa} + T_{d850hPa} - 2\left[T_{500hPa}\right] \tag{6}$$

Here '$T_{(850hPa)}$' is the temperature at 850 hPa, '$T_{d850hPa}$' is the dew point temperature at 850 hPa, and '$T_{(500hPa)}$' is the temperature at 500 hPa.

$$SWEAT = 12\left[Td_{850hpa}\right] + 20(TTI - 49) + 2(f8) + f5 = 125(S + 0.2) \tag{7}$$

Here '$Td_{(850hpa)}$' is the dew point temperature at 850 hPa, 'TTI' is the Total Total Index, '*f8*' and '*f5*' are the 850 hPa and 500 hPa wind speeds in knots, and 'S' is the sin of (500–850 hPa wind direction).

$$KI = \left(T_{850hPa} - T_{500hPa}\right) + T_{d850hPa} - \left(T_{700hPa} - T_{d700hPa}\right) \tag{8}$$

Here '$T_{(850hPa)}$' is the temperature at 850 hPa, '$T_{(500hPa)}$' is the temperature at 500 hPa, '$T_{d850hPa}$' is the dew point temperature at 850 hPa, '$T_{(700hPa)}$' is the temperature at 700 hPa, and '$T_{d700hPa}$' is the dew point temperature at 700 hPa.

4 Results and discussions

4.1 Synoptic analysis

Figure 1 illustrates the wind analysis, depicting the position of the trough over interior Karnataka extended up to mid-tropospheric levels on 31 August 2023. There are specific time periods during which the monsoon trough is situated at the base of the Himalayas. This positioning results in a significant reduction in rainfall across the majority of the country, while simultaneously causing an increase in rainfall along the Himalayas, as well as in certain regions of North East India and the Southern Peninsula. A cyclonic circulation was observed over North-east Bay of Bengal as well as adjacent areas reaching an altitude of 5.8 AMSL. This synoptic situation prevailed during breakdown monsoon season.

On August 31, 2023, Bengaluru encountered a significant weather event characterized by torrential rainfall and strong thunderstorms, which were attributed to the extension of an upper air trough reaching a height of ≈ 3 km. A precipitation measurement of 90 mm was recorded on this day. The formation of thunderstorms is facilitated by the presence of a surface trough and an upper air trough as Figures S1 and S2 in supplementary data. After conducting a wind examination,

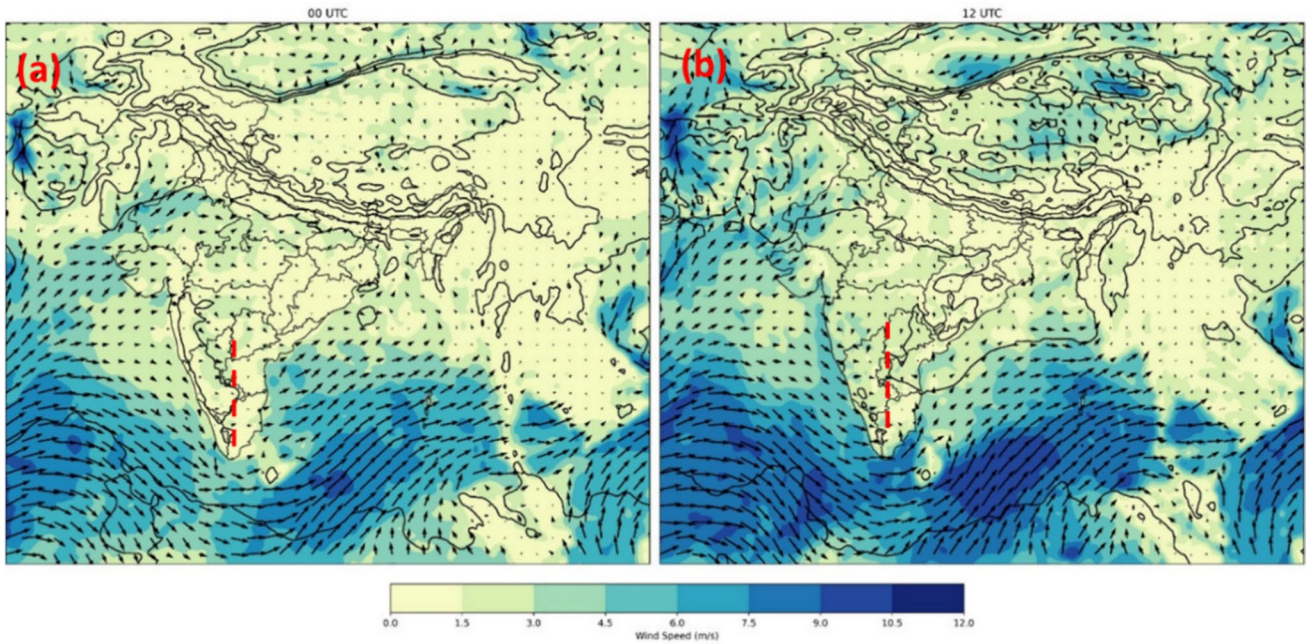

Fig. 1 ECMWF model surface wind analysis over Indian region for 31 August 2023 at **a** 00UTC and **b** 12UTC

the trough extended up to the mid-tropospheric levels in a north–south direction. Winds that originated in the Arabian Sea and blew from the north-west provided moisture to the interior of Karnataka. The trough was located at the pressure field's mean sea level and trough in wind field was extended up to 500 hPa level. The deep trough served as an inducement for the moisture to rise, and the moisture supply resulted in significant rainfall.

The prevailing surface temperature and humidity conditions are conducive to the formation of convective clouds. The potential reason contributing to precipitation is mechanical turbulence resulting from heightened surface roughness. Additionally, the presence of urban warm air, which generates additional sensible heat, may also play a role. Furthermore, atmospheric condensation nuclei suspended in the air could contribute to precipitation events.

4.2 Analysis of satellite images

The primary tools for detecting convective storms are satellite imagery and weather radars [27]. The cloud top brightness temperature (CTBT) obtained from INSAT-3D imagery on August 31, 2023 is presented in Fig. 2. DWR images of Chennai Radar for the period 1600 UTC to 2100 UTC on 31 August 2023 are shown in Fig. 3a–e. The Fig. 2 employed to ascertain variations in the quantity, altitude, and vertical spread of cloud formations. The weather systems and processes which occur at scales of horizontal dimensions generally range from 5 to several hundred kilometers known as mesoscale. The correlation between characteristics and temperature at the uppermost region of clouds, which is associated with low temperature, and precipitation levels varies to a certain degree [28]. Satellite imagery reveals the existence of extensive cloud cover over South interior Karnataka and its surrounding regions, characterized by deep clouds. These clouds exhibit a top cloud temperature as low as − 60 °C, indicating their significant vertical extent. Furthermore, the convective clouds observed in the area extended to the heights of 12 km. This also supported by the DWR images observed by Chennai DWR on 31 August 2023. The convective zone exhibited a state of instability in the region of South Interior Karnataka.

4.3 Thermodynamic features

Figure 4 depicts the skew-T diagram showing temperature and dew-point temperature in vertical profile along with thermodynamic indices. Up to 500 hPa level, there is sufficient moisture and the atmosphere is very unstable. The Tephi gram on August 31, 2023 at 00:00 UTC showed the CAPE values of 2153 J/kg and a CINE value of 0 J/kg, and all other indices values are shown in Table 1, which indicates that the whole of the atmosphere exhibited a state of significant instability. Similar results are found in thunderstorm event over Delhi on 25 May 2011 [12]. The study conducted over north-east Indian region by Mukhopadya et al. [15], threshold values of CAPE were reported to be 896.8 J/kg and K-index was recorded as 36.90 during thunderstorm events. Further, Kunz [29] and Peppler and Lamb [30] reported the threshold values for the K-index as being greater than or equal to 26.1 over Southwest Germany and greater than or equal to 20 over united states of America, respectively. Even though the K-index values are variable, in the present study, the lift index was recorded as − 4.37 and K-index as 36.90. Duraisamy et al. [10] provided that the crucial values of LI are less than 0 and KI are > 24 over Indian region. The results of lift index and K-index was also found to be favorable for the occurrence of thunderstorm over the Bengaluru region.

5 Summary and conclusion

The abundance of precipitation experienced in Bengaluru can be attributed mostly to the presence of a trough at mean sea level and an upper air trough located over interior Karnataka. The synoptic features indicate the transportation of a significant quantity of moisture from the Arabian Sea. In addition to thermodynamic indices and atmospheric instability, the synoptic aspects also contributed favorably to the initiation and development of convective clouds. Analyzed initially were the weather systems' development during the study period, using a sequence of satellite images. After isobaric study analysis, it was found that a trough dominated the interior parts of Karnataka. The study indicates that the thermodynamic indices such as CAPE (> 2000), CINE < (10), TTI (< 50) and high negative LI and SI values (< − 5) are favorable conditions for occurrences of thunderstorms over Bengaluru.

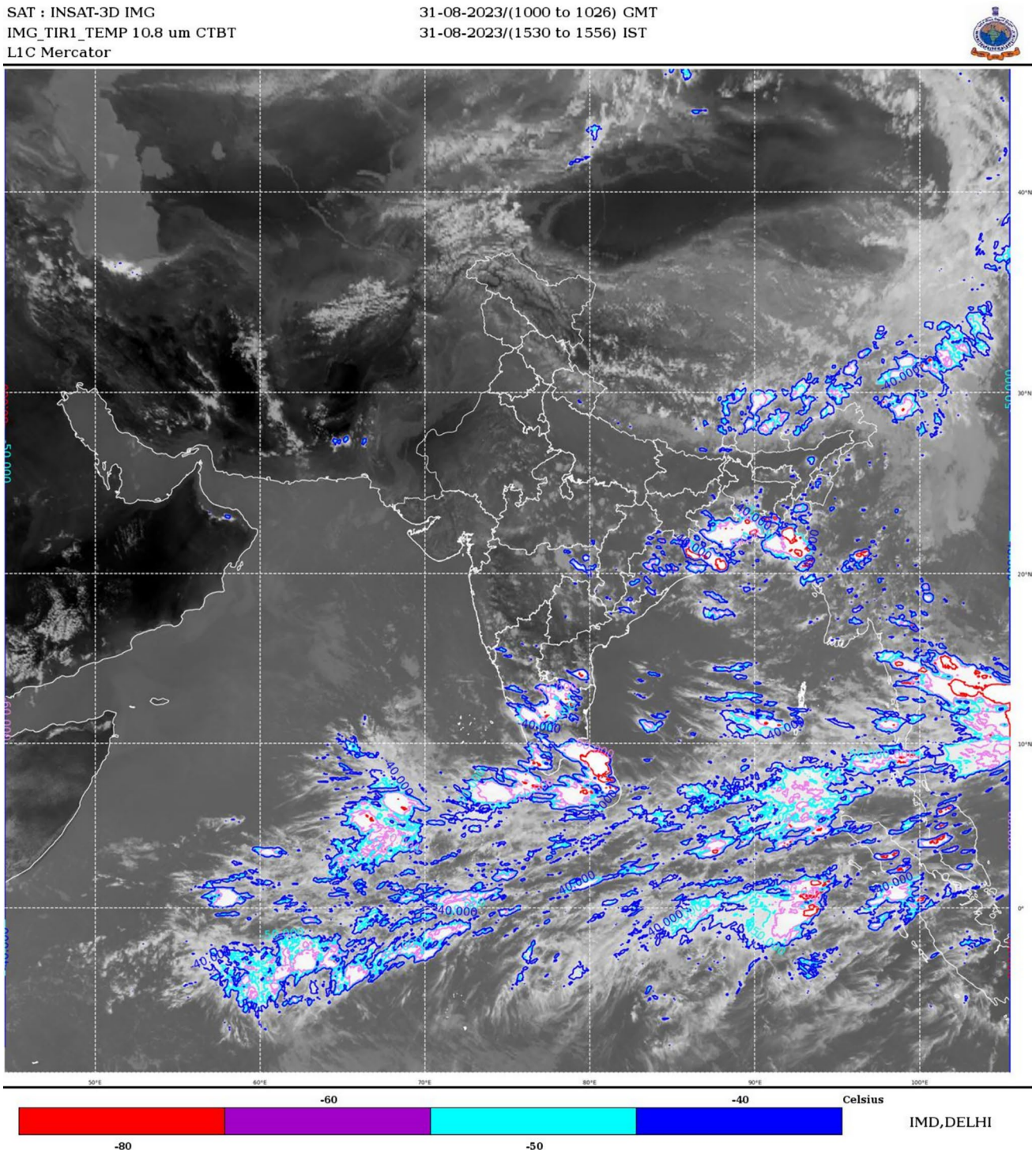

Fig. 2 Satellite image showing Cloud Top Brightness Temperature on 31 Aug 2023

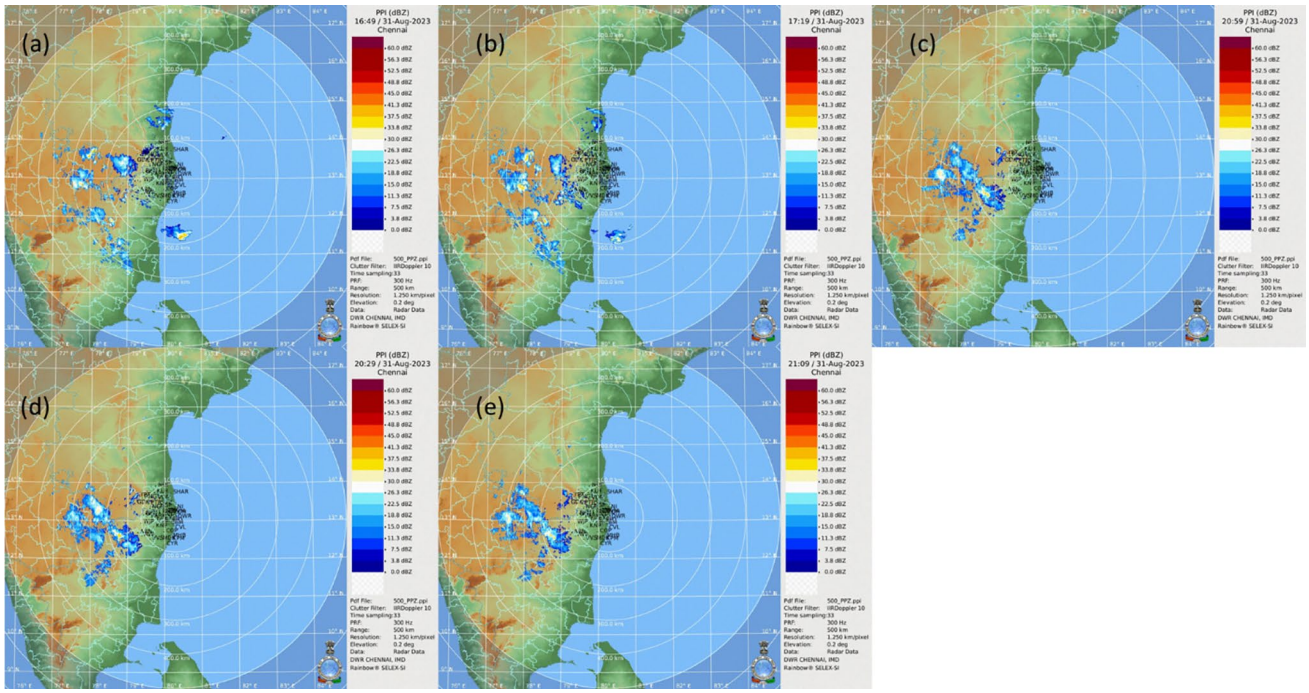

Fig. 3 Image showing the reflectivity (dbz) by thunderstorm cells over Bengaluru region observed by DWR Chennai at different UTC hours **a** 16:49, **b** 17:19, **c** 20:59, **d** 20:29 and **e** 21:09 on 31 August 2023

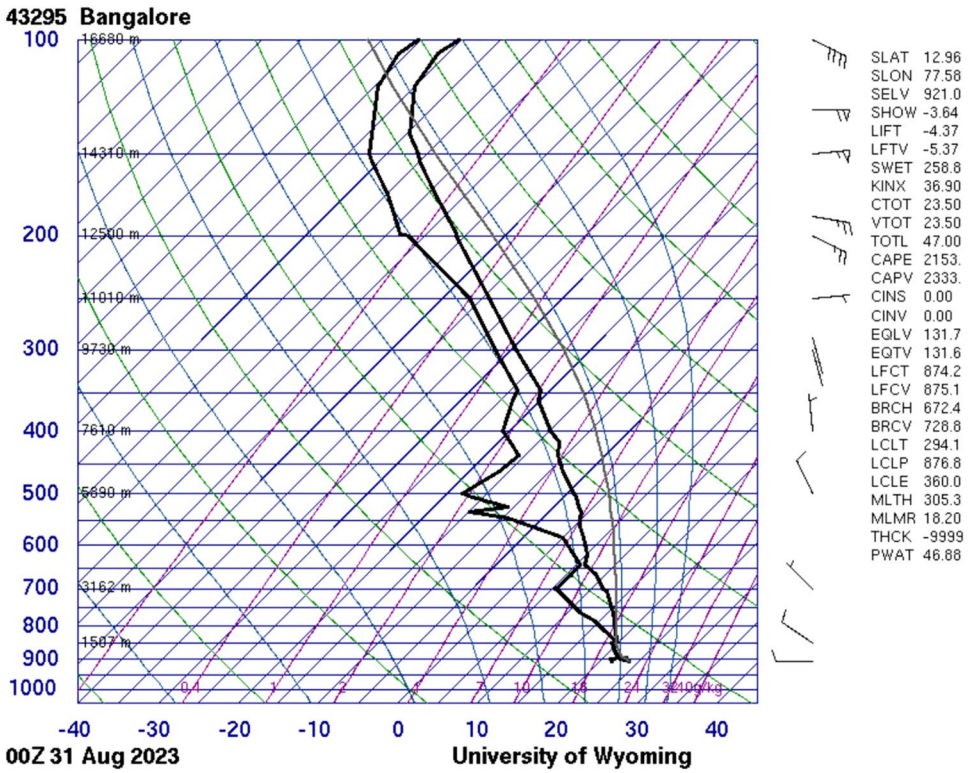

Fig. 4 Skew-T log-P diagram observed over Bengaluru during 31 August 2023 at 00 UTC

Table 1 Thermodynamic Parameters observed at 00 UTC over Bengaluru station on 31 August 2023

Indices	Value	Interpretation (Yavuz et al. [26])
Convective available potential energy (J/kg)	2153.12	1000 < CAPE < 2500, Unstable atmosphere
Convective inhibition energy (J/kg)	0.0	CIN < 100, Potential instability
Total Total Index (°C)	47.00	44 < TTI < 50, Thunderstorms likely occurred
Showalter index (SI)	− 3.64	− 6 < SI < − 3, Severe thunderstorms probable
Lifted index (°C)	− 4.37	LI < − 4, Severe thunderstorms possible
SWEAT index	258.81	200 < SWEAT < 400, Severe thunderstorms possible
K index (°C)	36.90	36 < KI < 40, Numerous thunderstorms,
Bulk Richardson Number	672.48	BRN > 45, Buoyancy dominates over shear

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Data availability Data available on request basis (csgoudapatil@gmail.com).

Declarations

Competing interests The authors declare that there is no competing interest related to this article.

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