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Rainfall Prediction Using CAPE and Surface Temperatures in Three Major Indian Cities

S. Sridevi [1, a)], K. Tarakeswara Rao [2, b)], Jayshree Das [3, c)], A. Narendra Babu [4, d)], Subrata Kumar Das [5, e)], M. Rajesh Yadav [6, f)], and P. S. Brahmanandam [7, g)]

[1]Department of Physics, Andhra University, Visakhapatnam 530017, India
[2] Department of Electronics, Sri Venkateswara College, Dhalula Kuan, New Delhi 110021, India
[3] Department of Electronics and Communication Engineering, B. V. Raju Institute of Technology, Narsapur 502313, India
[4] Department of Electronics and Communication Engineering, Lakkireddy Bali Reddy College of Engineering, Mylavaram 521230, India
[5] Indian Institute of Tropical Meteorology, Pune 411 008, India
[6] Department of Physics, Vishnu Institute of Technology (A), Bhimavaram 534202, India
[7] Department of Physics, Shri Vishnu Engineering College for Women (A), Bhimavaram 534202, India

[g)] Corresponding author: dranandpoula@svecw.edu.in, anand1576@gmail.com
[a)] sridevi.singarapu@gmail.com
[b)] ktarak7777@gmail.com
[c)] jayshree.das@bvrit.ac.in
[d)] narendraalur@gmail.com
[e)] skd_ncu@yahoo.com
[f)] rajeshyadav.m@vishnu.edu.in

Abstract: This study investigates the seasonal variation of radiosonde-derived convective available potential energy (CAPE) and their relationship with near-surface temperatures and rainfall over three Indian metropolitan stations with varying geographical settings. The radiosonde stations are Chennai (13° N, 80.18° E), a coastal station in southern India, Hyderabad (17.45° N, 78.46° E), a southern inland station, and Delhi (28.3° N, 77.1° E), a northern inland station. A distinct seasonal variation is found in CAPE which was associated with minimal magnitudes during winter followed by post-monsoon season, pre-monsoon season, and the monsoon season. The European Center for Medium Weather Forecasting (ECMWF) Reanalysis (ERA-Interim) CAPE also showed a distinct seasonal variation, as seen in the radiosonde-measured CAPE. A comparative study between CAPE and temperatures revealed a one-to-one correspondence, but no similarity was found between CAPE and rainfall data. The correlation coefficients (r) between CAPE and temperature at 1km show relatively higher values at all three stations during the study period, confirming the surface conditions affect the magnitude of CAPE. However, a low to moderate correlation existed between CAPE and the environmental lapse rate. Conversely, a poor to low correlation has existed between CAPE and rainfall, indicating that a warmer climate might be necessary, but not sufficient to have precipitation over any station.

Keywords: CAPE, Rainfall, Radiosonde, ECMWF, Correlation coefficients

INTRODUCTION

Convective available potential energy (CAPE) is an important parameter for understanding the origin and intensity of convection [1]. CAPE, a measure of the conditional stability of the troposphere to a finite vertical displacement, occurs predominantly during moist convection [2]. There are several studies on CAPE using radiosondes or balloon-borne instruments [3-10], although other meteorological instruments, including balloon-borne packets, satellites [11- 13], microwave radiometers (MWR), dropsondes [14-15, 10], and model-based data (European center for medium weather forecast (ECMWF), NCEP/NCAR reanalysis that is the National Centre for Atmospheric Research /United States National Centres for Environmental Prediction), [16] have been used to examine CAPE spatio-temporal variability and trends. Rainfall intensity is dictated not just by accessible moisture but also by atmospheric convection. Nevertheless, we are not aware of systematic investigations of how the convective available potential energy (CAPE) affects rainfall extremes. Further, a positive relation between CAPE and the near-surface temperature still prevails even in recent years. The relation between atmospheric variables and precipitation is still not well understood, particularly regionally and locally [17].

The novelty of the present is that geographical diversity. To elaborate, the present study spans diverse geographic locations, providing insights into how CAPE behaves in coastal versus inland settings in both southern

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and northern India. In addition, the present study finds a strong correlation between CAPE and near-surface temperatures, confirming that surface conditions significantly influence CAPE magnitudes across all three stations. The present research objectives are:

a) To understand the relation between CAPE and near-surface temperatures during 2018-2020 over three Indian metropolitan stations.

b) To verify the relationship between CAPE and temperature, CAPE and the environmental lapse rate, and CAPE vs. rainfall.

The organization of this paper is as follows: Section 2 presents various data sets used in this present study. Section 3 contains results and discussion, wherein section 3.1 presents monthly variations of radiosonde CAPE and ECMWF CAPE, section 3.2 will have the relation between CAPE vs. temperatures and CAPE vs. rainfall, and section 3.3 presents correlation coefficient statistics between CAPE and temperature and CAPE and the environmental lapse rate. The conclusions are summarized in section 4.

DATASETS

This study has considered radiosonde data between January 2019 and December 2020 measured over Chennai (13.00° N, 80.18° E), Delhi (28. 58° N, 77. 20° E), and Hyderabad (17.45° N, 78.46° E). Figure 1 shows the elevation (meters) of three Indian stations (shown with star symbols). Chennai is a tropical coastal station facing the Bay of Bengal, Delhi is a sub-tropical and semi-arid inland station, and Hyderabad is a tropical inland station. Radiosonde data were collected at 0000 (0530 local time, LT) and 1200 (1730 LT) GMT hours. The study utilizes high-resolution daily rainfall data [18] from India Meteorological Department (IMD) and ERA-Interim reanalysis datasets [19], providing detailed weather and surface condition parameters at 0.25° × 0.25° spatial resolution, including CAPE products.

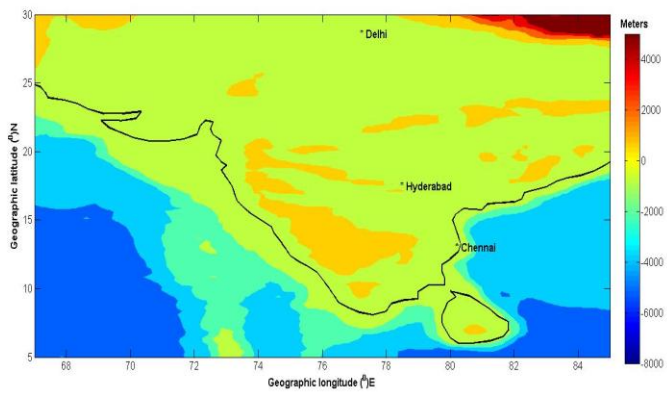

FIGURE 1. *Elevations of three Indian stations used in this study*

RESULTS AND DISCUSSION

Monthly Variations of Radiosonde CAPE and ECMWF CAPE

Figure 2a (top panel) shows the monthly changes in CAPE (Convective Available Potential Energy) measured with radiosondes over Chennai from January 2018 to December 2020. One can see a clear seasonal pattern in CAPE. For example, CAPE is very low in winter (December to February), followed by post-monsoon (October to November), pre-monsoon (March to May), and monsoon seasons (June to September). CAPE values as high as 3000 J/kg were recorded on three days during the pre-monsoon season of 2018 and the monsoon season of 2020. Figure 2b (top panel) shows monthly changes in CAPE derived from ECMWF (ERA-Interim) data over Chennai from January 2018 to August 2019. The ECMWF CAPE data closely matches the radiosonde data, but with slightly lower values. This is consistent with previous findings [13] showing that ECMWF tends to underestimate CAPE compared to radiosonde measurements. Like the radiosonde data, the ECMWF CAPE shows very low values in winter, followed by post-monsoon, pre-monsoon, and monsoon seasons, indicating a clear seasonal pattern similar to the radiosonde measurements.

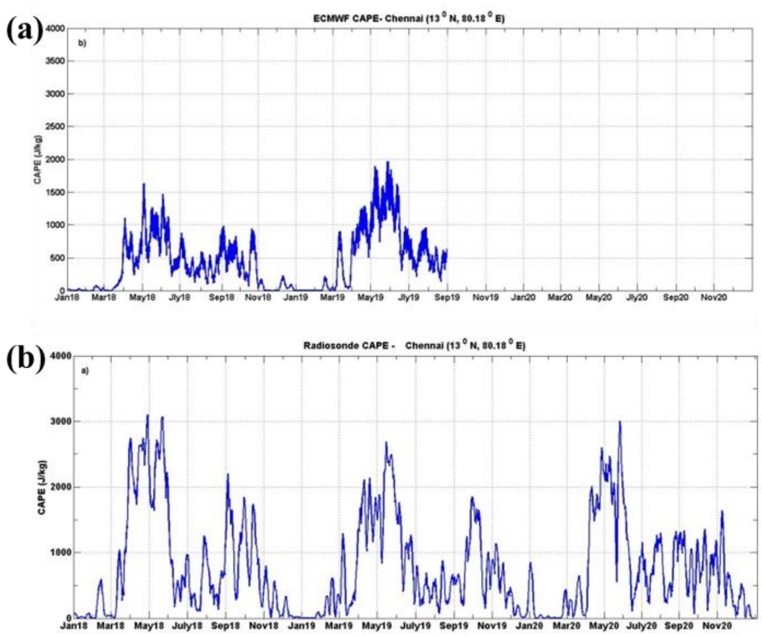

FIGURE 2. *Monthly variations of (a) ECMWF CAPE and (b) radiosonde CAPE over Chennai, India.*

Figure 3a (bottom panel) shows monthly variations of radiosonde derived CAPE over Delhi (28.3^{0}N, 77.1 ^{0}E) between January 2019 and December 2020. Like Chennai's monthly variations, CAPE over Delhi also shows a distinct seasonal variation with extremely low values during the winter seasons, followed by the post-monsoon seasons, pre-monsoon seasons, and monsoon seasons. However, the maximum magnitudes associated with CAPE are lower than what we observed in Chennai. The monthly variations of ECMWF CAPE over Delhi are presented in Figure 3b (top panel), wherein one can see a distinct seasonal variation similar to the radiosonde CAPE variations, though CAPE magnitudes associated with them show a completely different picture. This means that minimal CAPE values are noticed in the winter season, followed by the post-monsoon season, pre-monsoon seasons, and monsoon seasons. Overall, CAPE value hardly reached a magnitude of 1300 J/kg once.

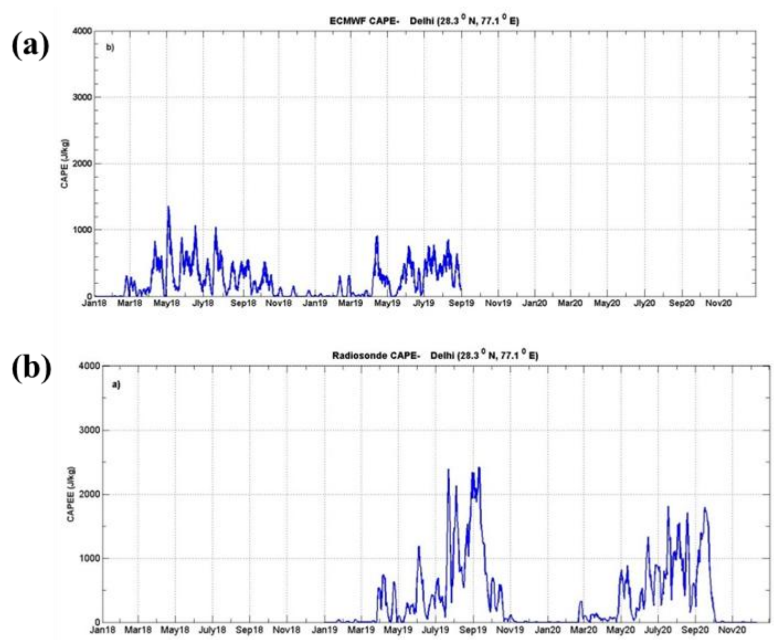

FIGURE 3. *Monthly variations of (a) ECMWF CAPE and (b) radiosonde CAPE and over Delhi, India.*

The bottom panel of Figure 4a shows monthly variations of radiosonde CAPE over Hyderabad from January 2018 to December 2019. Unlike Chennai and Delhi, Hyderabad's CAPE varies differently each month. CAPE decreased during the 2018 monsoon but not in 2019. Both winters show very low CAPE, while pre-monsoon seasons have higher values, followed by the post-monsoon and monsoon seasons. The top panel of Figure 4b shows ECMWF CAPE, which also has clear seasonal variations, with the lowest values in winter. There is a large difference in magnitudes, with ECMWF CAPE reaching over 1600 J/kg in the pre-monsoon season.

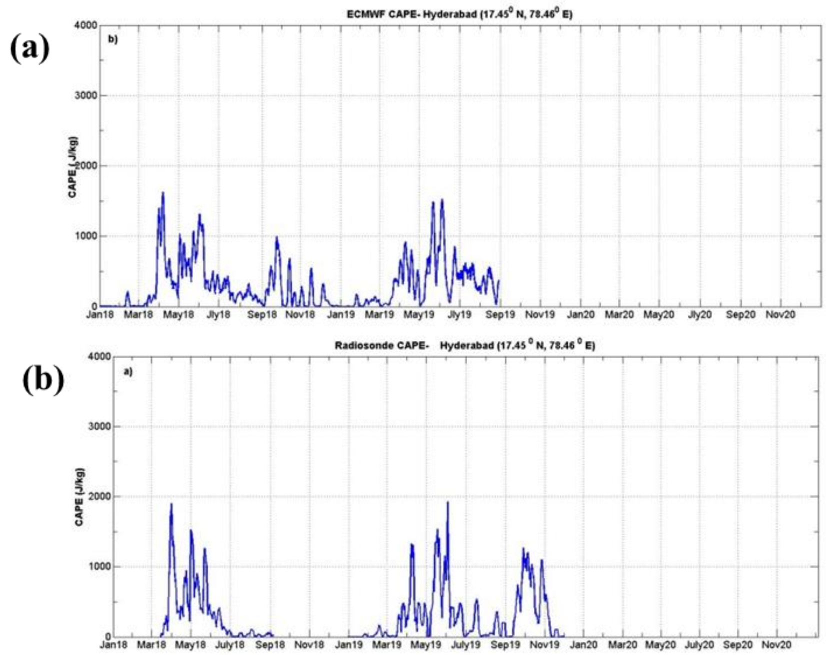

FIGURE 4. *Monthly variations of (a) ECMWF CAPE and (b) radiosonde CAPE and over Hyderabad, India.*

The huge difference in CAPE magnitudes over these three stations could be due to different thermodynamical phenomena that exist over the respective stations. Being a coastal station, the Chennai region could be highly controlled by convective activity as it is very near to the Bay of Bengal, so larger CAPE can be witnessed over Chennai compared to the other two inland stations (Delhi and Hyderabad). A similar scenario is also reported for CAPE values over Kolkata (22.3^o N, 88.2^o E) [8], a coastal station in the northeast region of India. Research conducted by [13] used the INSAT-3D, radiosonde, and ECMWF CAPE over the entire Indian region for three years (April 2014- March 2017) revealed that ECMWF CAPE never exceeded 2000 J/kg in any season, while INSAT-3D and radiosonde CAPE could reach as high as 4000 J/kg. It is known that the spatial resolution of ECMWF reanalysis data is coarse compared to the observations and that could be the reason for ECMWF CAPE low values [13].

Relation of CAPE with Temperatures and Rainfall

We present comparative studies between CAPE and temperature at different altitudes and CAPE vs. rainfall to understand their inherent relations over three Indian stations. The motivations behind presenting temperatures at different altitudes are that CAPE will be affected by temperature and it is expected that there is always a positive relation exists between near-surface temperatures and CAPE in the tropics [20-21]. Figure 5 shows monthly variations of average temperatures at 1 km, 2 km, 3 km, 4 km, and 5 km (Figure 5a) vs. CAPE (Figure 5b) and rainfall (Figure 5c) over Chennai.

A mere look at Figures 5a and 5b show that a great similitude exists between them and a seasonal variation also presents in temperature variations at all altitude ranges in similar lines with CAPE seasonal variations. Interestingly, almost a similar wavy nature, which is due to diurnal and seasonal variations forced by solar energy, can be seen in temperature variations at different altitudes and, as expected, their magnitudes are found to have shown significant differences with the progress of altitudes. For instance, there is a consistent temperature difference of about 5-6 ^{0}C between 1 km and 3 km. This 1 km and 3 km temperature differences represent the atmospheric stability [22]. The temperature difference between approximately 978 hPa and 776 hPa levels indicates the lower tropospheric lapse rate [23].

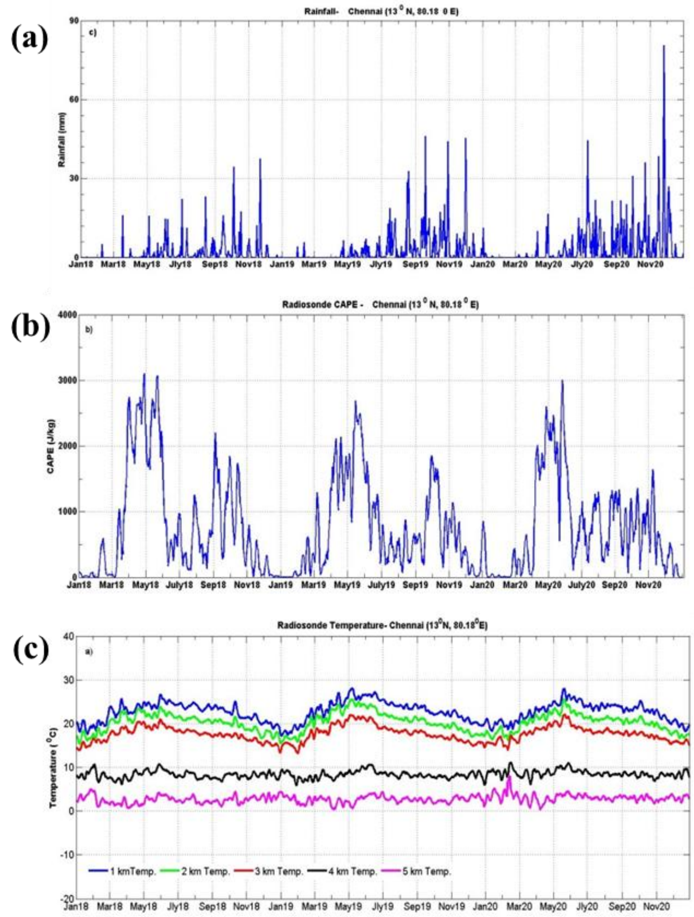

FIGURE 5. *Monthly variations of (a) rainfall, (b) CAPE, and (c) temperatures at 1 km, 2 km, 3 km, 4 km, and 5 km, over Chennai (13^0 N, 80.18^0 E), India between January 2018 and December 2020.*

Rainfall in Chennai has increased since April 2018, with pre-monsoon depressions possibly contributing [13]. Rainfall continued until November in 2018, and until January in 2019 and 2020. Only two days in November 2020 had heavy rainfall, while most days had light to moderate rain. There is a low positive correlation (r = 0.20) between CAPE and rainfall. Figure 6 shows Delhi's monthly average temperatures at various altitudes (Figure 6a), CAPE (Figure 6b), and rainfall (Figure 6c). Temperatures show seasonal variation. Rainfall increases from mid-May to June, peaking between June and September. Winter rains in Delhi, especially from January to March, are linked to western disturbances [24]. The correlation between CAPE and rainfall in Delhi is also low (r = 0.1).

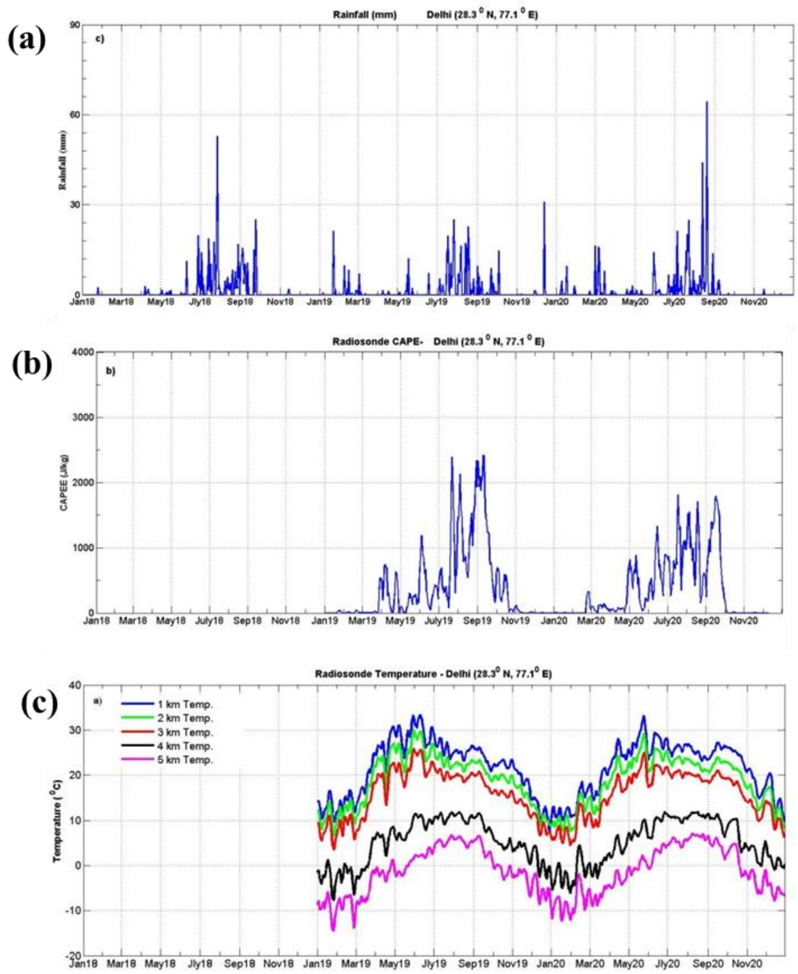

FIGURE 6. *Monthly variations of (a) rainfall. (b) CAPE, and (c) temperatures at 1, 2, 3, 4, and 5 km over Delhi, India.*

Figure 7 shows monthly variations of average temperatures (Figure 7a) at 1 km, 2 km, 3 km, 4 km, and 5 km, CAPE (Figure 7b) and rainfall (Figure 7c) over Hyderabad. Similar to Delhi and Chennai variations, temperatures at 1 km, 2 km, and 3 km altitude ranges show a consistent wavy nature and a dominant seasonal variation. However, the average temperatures at 4 km and 5 km from March 2019 to September 2019 (six months) are not after the underneath altitude variations. As it is known that the larger the CAPE the higher the energy coupling from lower to upper altitudes via wave coupling [8] and such an energy coupling could have, therefore, affected CAPE. But, no such scenario is observed for CAPE from March 2019 to September 2019 (see Figure 7b) and, hence, the causative mechanisms of this non-wavy nature of temperatures at 4 and 5 km cannot be understood right here. The rainfall data at Hyderabad depicts increasing trends starting by early May and reached peak values between June and October in most of the years.

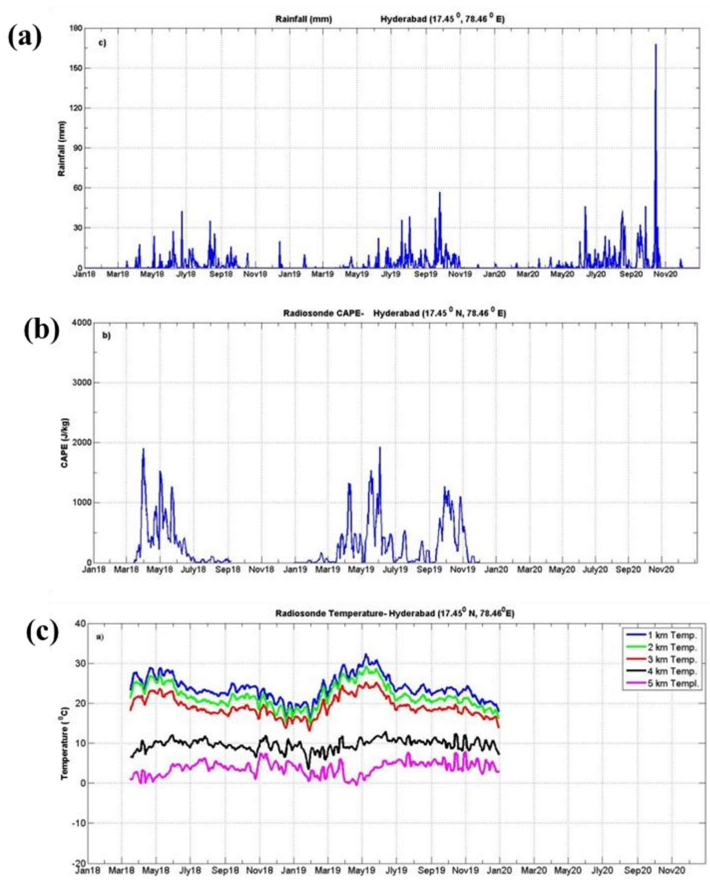

FIGURE 7. *Monthly variations of (a) rainfall, (b) CAPE, and (c) temperatures at 1 km, 2 km, 3 km, 4 km, 5 km over Hyderabad (17.45^0 N, 78.46^0 E), India.*

Temperature and Lapse Rate Variability in Relation to CAPE

Figure 8 shows correlation coefficients between CAPE and temperature at 1 km at Chennai (top panels), Delhi (middle panels), and Hyderabad (bottom panels) in 2018, 2019, and 2020.The correlation coefficients at Chennai are found to be 0.52 (2018), 0.67 (2019), and 0.70 (2020), at Delhi, which are 0.47 (2019), 0.56 (2020), while at Hyderabad, 'r' values are 0.64 (2018) and 0.51(2019), respectively. The highest correlation between CAPE and near-surface temperatures can be expected based on the following argument. As the air temperature increases, a sign of positive buoyancy index, the CAPE also increases that may significantly affect the ensuing convection [21].

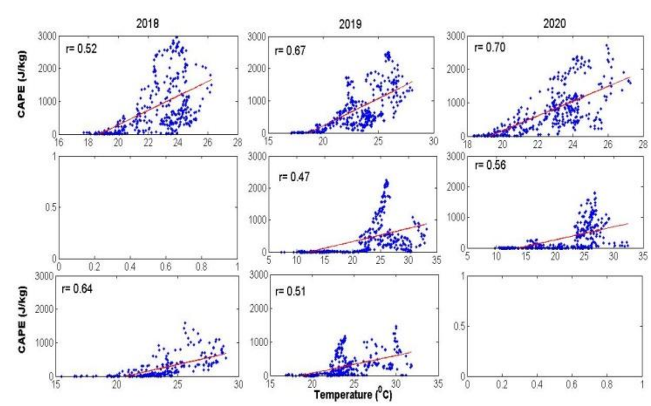

FIGURE 8. *Correlation coefficients of CAPE vs. temperature at 1 km over Chennai, Delhi, and Hyderabad (top, middle, and bottom panels) for 2018, 2019, and 2020. The correlation coefficients are denoted by 'r' in each panel.*

Figure 9 shows the correlation coefficients between CAPE and lapse rates at Chennai, Delhi, and Hyderabad for 2018-2020. The coefficients are as follows: Chennai: -0.02 (2018), 0.24 (2019), 0.29 (2020), Delhi: 0.01 (2019), -0.01 (2020), Hyderabad: 0.16 (2018), 0.47 (2019).These values indicate poor to moderate correlations. Previous research found a correlation of 0.33 between CAPE and lower tropospheric lapse rates [23], suggesting that CAPE and CIN are influenced by tropospheric parameters and boundary layer moisture. To fully understand the relationship, additional data is needed.

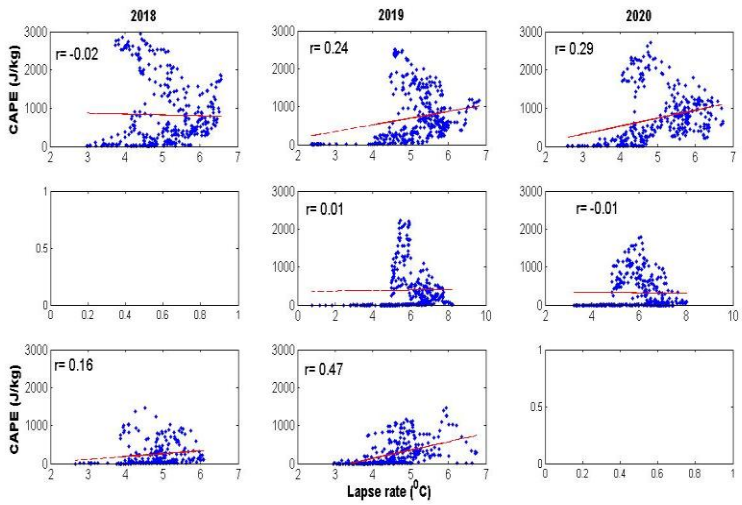

FIGURE 9. *Correlation coefficients of CAPE vs. lapse rate at Chennai (top panels), Delhi (middle panels) and Hyderabad (bottom panels) for 2018, 2019, 2020. The correlation co-efficients are denoted by 'r' in each panel.*

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CONCLUSION

A comparative analysis of radiosonde and ECMWF CAPE over three Indian cities shows distinct seasonal variations, with minimum values in winter and increasing through post-monsoon, pre-monsoon, and monsoon seasons. Radiosonde CAPE often reaches 3000 J/kg, while ECMWF CAPE rarely exceeds 2000 J/kg. Over the years, ECMWF CAPE values increased, unlike radiosonde CAPE. A low correlation between CAPE and rainfall was observed from 2018 to 2020, highlighting the complex relationship between precipitation and atmospheric parameters. The Clausius-Clapeyron relation suggests a 6.8% increase in rainfall per 1°C rise in temperature [26-27], but this does not apply uniformly across regions [27]. The role of convective inhibition energy (CIN) must also be considered [28], as large negative CIN values can hinder rainfall despite high CAPE. Thus, a warmer climate alone is not sufficient to guarantee precipitation.

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