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Pre-monsoon thunderstorm season climatology of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) over Eastern India

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सार – मॉनसून पूर्व ऋतु के दौरान पूर्वी भारत (ओडिशा, पश्चिम बंगाल और झारखंड) में जहां गर्ज के साथ तूफान अक्सर आते हैं और ये विनाशकारी होते हैं, उपलब्ध संवहनी संभावित ऊर्जा (सीएपीई) और संवहनी अवरोध (सीआईएन) से से जलवायु विविधताओंका इस शोध में विश्लेषण किया गया है। इसमें यूरोपियन सेंटर फॉर मीडियमरेंज वेदर फोरकास्ट फोरकास्ट (ECMWF) **के** 1987-2016 **के** ERA-5, **रीएनालिसिसडेटा का उपयोग किया गया है: इस क्षेत्र में गर्ज के साथ तूफान वाली घटनाओं के बारे में जानकारी भारत मौसम विज्ञान विभाग** (IMD) **से प्राप्त की गई है। यह अध्ययन मॉनसून मॉनसून पूर्व ऋतु के दौरान पूर्वी और उत्तर-पूर्वी भारत में संवहनी गतिविधिको समझने के लिए जलवायु संबंधी मानचित्र तैयार करने में पूर्वानुमानकर्ताओं की मदद करता है। अध्ययन से पूर्वानुमानकर्ता को टीडी की संभावना का आकलन करने में भी मदद मिलती है, जिसमें रेंज विशिष्टमान होते हैं, उदाहरण के लिए कोलकाता क्षेत्र में टीडी के दौरान सीएपीई मान मान** ≥2500 **से** ≥3000 **जूल/किलोग्राम हैं जबकि सीआईएन मान** ≥350 **से** ≥400 **जूल/किलोग्राम हैं। ओडिशा और पश्चिम बंगाल के तटीय क्षेत्रों के साथ-साथ पश्चिमोत्तर बंगाल क्षेत्र की सीमा से लगे झारखंड में सीएपीई** (CAPE) **अधिक है और सीआईएन का मान कम है। गैर-पैरामीट्रिक मान-केंडल परीक्षण का उपयोग कर के सीएपीई और सीआईएन का प्रवृत्ति विश्लेषण किया गया है, जो टीडी और एनटीडी के लिए राज्यों के विभिन्नक्षेत्रों के लिए समय के साथ सूचकांकों के एक स्पष्ट परिवर्तन को दर्शाता है। सीएपीई टीडी के दौरान ओडिशा और पश्चिम बंगाल के तटीय जिलों और संपूर्ण पश्चिम बंगाल में** 12 **यूटीसी पर एनटीडी में वृद्धि की प्रवृत्ति को दर्शाता है। एनटीडी के मामले ओडिशा** (0000 **और** 1200 **यूटीसी दोनों**) **और पश्चिम बंगाल में** 0000 **यूटीसी पर कमी की प्रवृत्ति को दर्शाते हैं। सीआईएन पूरेओडिशा में टीडी के लिए प्रवृत्ति और एनटीडी के लिए घटती प्रवृत्ति को दर्शाता है, जबकि पश्चिम बंगाल के लिए टीडी के दौरान तटीय क्षेत्रों के लिए रुझान सकारात्मक हैं और एनटीडी के दौरान पूरे राज्य में नकारात्मक हैं। झारखंड के लिए सीएपीई और सीआईएन दोनों के मान एनटीडी के दौरान राज्य में वृद्धि की प्रवृत्ति को दर्शाते हैं, जबकि टीडी के लिए दोनों वृद्धिकमी की प्रवृत्ति को दर्शा रहे हैं। मॉनसून पूर्व ऋतु के दौरान गर्ज के साथ तूफान की अधिक संभावना वाले क्षेत्रों को समझने के लिए उस क्षेत्र में प्रेक्षित गर्ज के साथ तूफान के कारणों के विश्लेषण को समझना होगा।**

ABSTRACT. The present work analyses climatological variations of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) over the eastern India (Odisha, West Bengal and Jharkhand) during the pre-monsoon season, where thunderstorms are frequent and disastrous. The work sutilises European Centre for Medium-Range Weather Forecast (ECMWF) re-analysis data : ERA-5for 1987-2016, supplemented with information about thunderstorm occurrences over the region from India Meteorological Department (IMD). The study helps to the forecasters to prepare climatological maps to understand the convective activity over eastern and north-eastern India during pre-monsoon season. The study also helps to forecasters to assess the likelihood of TD, with range specific values, *e.g.*, for Kolkata region the CAPE values are ≥2500 to ≥3000 J/kg while the CIN values are ≥350 to ≥400 J/kg during the TD. The coastal areas of Odisha and West Bengal, along with the Jharkhand bordering the northern West Bengal region, have higher CAPE and lower CIN values. The trend analysis of CAPE and CIN has been performed using the non-parametric Mann-Kendall test, which shows an apparent transformation of indices over time for different regions of states for TD and NTD. CAPE shows an increasing trend over the coastal districts of Odisha and West Bengal during TD and for the whole of West Bengal during 1200 UTC NTD. The NTD cases show a decreasing trend over Odisha (both 0000 and 1200 UTC) and 0000 UTC over West Bengal. CIN shows an increasing trend for TD and decreasing trend for NTD over whole Odisha, whereas, for West Bengal, trends are positive for coastal regions during TD and negative on the entire state during NTD. For Jharkhand, both the CAPE and CIN values show an increasing trend over the state during NTD, whereas for TD, both increasing/decreasing trends are visible. The analysis complements the observations of thunderstorm occurrence over the region to understand areas with higher potential of thunderstorm occurrence during pre-monsoon season.

Key words – Thunderstorm, CAPE, CIN, Climatology, Trend analysis.

1. Introduction

Thunderstorms are characterised as high downpour events accompanying thunder, gust and lightning in a brief time frame (Sahu *et al*., 2020a). The precipitation type associated with thunderstorms might be hail, rain, snow and occasionally without any rainfall (Williams, 2001). Atmospheric constraints (*e.g*., humidity, temperature, wind speed and direction, the pressure of the associated region) may change with these thunderstorms, with the extent of change depending on the severity of these thunderstorms (Tyagi, 2012; Tyagi *et al*., 2013a; Tyagi and Satyanarayana, 2019). Severe thunderstorms have been accounted for universal causalities (*e.g*., damage to the structures, buildings, loss of human life and above all, to the ecosystems) and initiating tornadoes (Goliger and Milford, 1998; Doswell III, 2003). Researchers utilised in-situ observations, satellite data and Doppler Weather Radar (DWR) imageries along with numerical simulations for understanding the genesis and propagation of these thunderstorms (Kalsi, 2002; Purdom, 2003; Sinha and Pradhan, 2006; Mukhopadhyay *et al*., 2009; Arora and Srivastava, 2010; Pradhan *et al*., 2012; Chaudhuri *et al*., 2014; de Coning *et al*., 2015; Goyal *et al*., 2017).

If one has surface observations with vertical levels, one can use the stability indices (accounting for the stability of the atmosphere) for understanding the thunderstorm dynamics over an area (Peppier, 1988). The thermodynamic indices deal with the physical and dynamical progression of the atmosphere by calculating potential, conditional, latent and convective instability for providing a fair understanding of the conducive conditions to cause a thunderstorm event (Sahu *et al*., 2020b). Thermodynamic indices are widely accepted to improve the forecasting of thunderstorm and related rainfall events for a long time (Schultz, 1989; Sadhukhan *et al*., 2000; Haklander and Delden, 2003; Madhulatha *et al*., 2013; Viceto *et al*., 2017). The most common thermodynamic indices used for understanding the convective progression over any region are Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) (Murugavel *et al*., 2014; Westermayer *et al*., 2017; Liu *et al*., 2020).

Though whole India experience thunderstorms, occurrence is high over eastern (parts of Bihar, Jharkhand, Odisha, West Bengal) and north-eastern (Arunachal Pradesh, Assam, Meghalaya, Manipur, Mizoram, Nagaland, Tripura) regions of India for the pre-monsoon (March-May) season (Rao and Raman, 1961; STORM Science Plan, 2005; Tyagi *et al*., 2011; Roy *et al*., 2019; Sahu *et al*., 2020a). The thermodynamic indices values differ for thunderstorm events over the central and north-west India to the eastern India, despite favourable deep convection (Srivastava and Sinha Ray, 1999). The occurrence of thunderstorms over north-west India is mainly associated with the western disturbances, whereas the north and eastern India thunderstorms are associated with deep convective activities during summer season (Srivastava and Sinha Ray, 1999; Das, 2015). The CAPE values over north-western India ranges from ~150-1500 J/kg, ~50-80 J/kg over central India and ~2000-3000 J/kg over eastern and north-eastern India. The CIN values over north-western India ranges from ~300-450 J/kg, ~480-700 J/kg over central India and ~85-400 J/kg over eastern and north-eastern India (Srivastava and Sinha Ray, 1999). The thunderstorms over eastern and north-eastern India are more catastrophic in nature and locally known as ‘Kal-Baishakhi’ or Nor’westers as they move from north-west to south-east (Chaudhari, 1961; Gupta, 1952; Chaudhuri *et al*., 2013). Srivastava and Sinha Ray (1999) investigated the role of CAPE and CIN on controlling convective activities over India and found that convective activities generally showed high/low values of CAPE/CIN during April 1997 over different parts of India. However, the north-eastern region is not following this pattern and lower CAPE values are found to be associated with thunderstorm events. Based on the previous studies, we can argue that CAPE values are not the only decider about TD or NTD, as it is a complex interaction process of land, ocean and atmosphere. North-east areas are mainly associated with capping inversion type of situation in many TD cases. Choudhury (2006) suggests that minimising CIN is critical for the origin of convective events, but neither maximising nor minimisation of convective available potential energy (CAPE) is essential. During the SAARC STORM project, the pre-monsoon thunderstorm aspects over India using Radiosonde, rawinsonde, Doppler Weather Radar has been widely explored (Das *et al*., 2014; Das, 2015). Various published works have analysed the thermodynamic state of the atmosphere with the visual representation of CAPE/CIN and the calculation of several other indices (Das, 2010; Tyagi *et al*., 2013c; Das *et al*., 2014; Das, 2015).

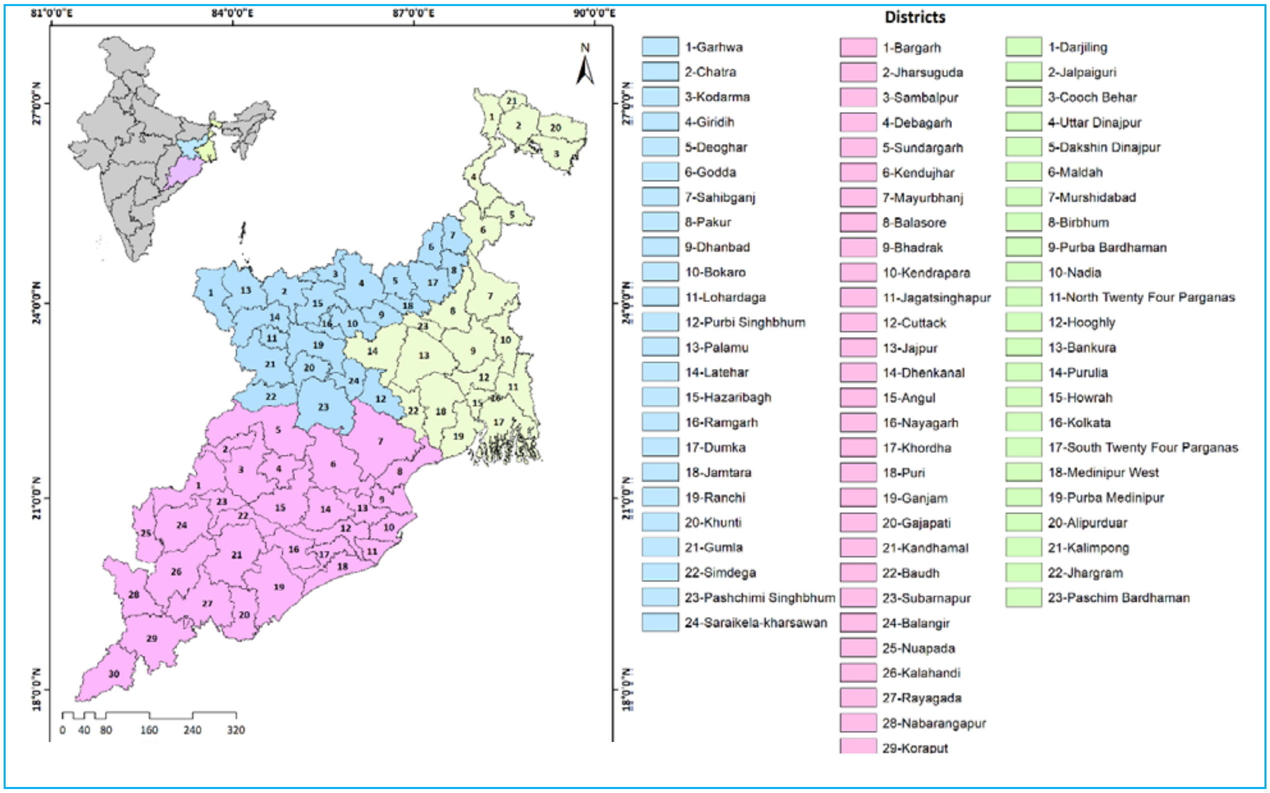

Fig. 1. Study Area. The eastern India states (Odisha, West Bengal and Jharkhand) are marked in different colours with their respective location on the map of India in the inset. Each district has been assigned a number and the index depicts the name associated with numbers for districts

The eastern and north-eastern India pre-monsoon thunderstorms are well explored for more than a century (*e.g.*, Buckland, 1905; Krishnamurthy, 1965; Kumar, 1992; Kar and Bondhyopadhyay, 1998; Santhosh *et al.*, 2001, Tyagi *et al.*, 2012; Tyagi and Satyanarayana, 2013a; Tyagi and Satyanarayana, 2013b; Tyagi and Satyanarayana, 2014a; Tyagi and Satyanarayana, 2014b, Sahu *et al.*, 2020a). The understanding about these thunderstorms have been developed using synoptic analysis, point observations and analysis of *in-situ* data, satellite or model performance analysis for simulating these thunderstorms (Litta and Mohanty, 2008; Madala *et al.*, 2013; Tyagi and Satyanarayana, 2015; Madala *et al.*, 2016). There are few works available for climatology based on the frequency of occurrence for these events (Tyagi, 2007; Mahanta and Yamane, 2020). Understanding the importance of thermodynamic indices for the nowcasting of these Nor'westers over eastern and north-eastern India, there are few attempts to develop a new index (Chaudhuri and Middey, 2012; Samanta *et al.*, 2020). The use of radiosonde data to understand long-term variability in these indices is one method adopted by researchers over the region (Sahu *et al.*, 2020a; Sahu *et al.*, 2020b). Though the various studies deal with long-term climatology of different indices using *in-situ* observations over eastern and north-eastern India, the utilisation of re-analysis data for calculating climatology of these indices considering thunderstorm occurrence over the region is absent. The global climatology of CAPE/CIN using ERA-40 data (Riemann-Campe *et al.*, 2009) and using ERA-5 data (Taszarek *et al.*, 2021) are available, which shows increasing trends of convective environments over tropical regions. However, the climatology with the inclusion of thunderstorm information over eastern India is absent.

The present work attempts to develop a climatology of CAPE and CIN for 1987-2016 over eastern India by combining the thunderstorm occurrence information for any particular day over different locations. This work aims to identify/categorise the CAPE and CIN variations on thunderstorm and non-thunderstorm days and project the trends of these thermodynamic indices during the study period with the climate change over the Eastern Indian regions. The trend of CAPE and CIN variations for the study period has been studied to understand the impact of changing climate scenarios and thunderstorm occurrence (frequency and intensity) changes. This paper is arranged as follows: Section 2 represents the study area, while section 3 features the data description and methodology, in section 4, we have presented the results and discussions and lastly, in section 5, we have ended with a summary of this work.

2. Area of study

The present study is focused on three states of eastern India: Odisha, West Bengal and Jharkhand, as appeared in Fig. 1. A concise description of the three states is as follows.

2.1. *Odisha*

The state Odisha (previously Orissa) is located in the east shoreline of eastern India, with temple city Bhubaneswar as its capital. The state shares borders in the West with Chhattisgarh, north with Jharkhand and West Bengal and in the south with Andhra Pradesh. It has a coastline of 485 km alongside the Bay of Bengal. It covers 4.87% of the whole extent of India, *i.e*., 155,707 km^2. The state has a population of 41,974,218 with a population density of 270 km^2 (Census of India, 2011). The state covers 51,619 km^2 areas of forest (Forest Survey of India report, 2019). The coastal plains of Odisha spread from north to south (*i.e*., from Subarnarekha River to Rushikulya River). The state is vulnerable to cyclonic activity and surrounded by Valleys and Mountain ranges. It experiences the Pre-monsoon season from March-May, South-West (SW) monsoon season from June to September, North-east monsoon from October to December and winter from January to February. The state experiences the tropical wet and dry climate (tropical Savanna climate) (Koppen climate classification, Aw) (Peel *et al*., 2007). The state encountered severe thunderstorms in the pre-monsoon season. On a particular note, the capital city Bhubaneswar experiences 77.4 thunderstorms in a year; specifically, the city receives 17.7 thunderstorms in the Pre-monsoon season (Tyagi, 2007).

2.2. *West Bengal*

West Bengal is the eastern state of India situated alongside the Bay of Bengal with Kolkata (previously Calcutta) as its capital city which is located near the Hooghly River. The state covers an area of 88,752 km^2 and also the seventh most populous state of India. The state population is 91, 3477,736 and the population density is 1029 km^2 (Census, 2011).The state surrounded by different states like Assam, Bihar, Jharkhand, Odisha and Sikkim. It also neighbours some countries like Nepal and Bhutan in the north and Bangladesh in the east. The state comprises the Ganges delta, Sunderbans delta and Darjeeling, the hill region of Himalaya. The Siliguri corridor,also known as 'Chicken's neck', is also located in this state. The critical river of this state is the river Ganges which separate into two branches in which one enters Bangladesh as the Padma and another through Bhagirathi and Hooghly River. The state experiences tropical savanna in the south and humid subtropical in the north (Koppen's Climate Classification Aw and As). It experiences four seasons' summer, rain, winter and autumn. It gets the BOB branch of the Indian monsoon, which is again circulated from south-east to north-west directions. During June to September, the monsoon brings heavy rainfall, *i.e*., more than 250 cm. The temperature ranges from 38 °C to 45 °C as the highest and in winter, the temperature is 15 °C for the state. In the pre-monsoon season, the state encounters thunderstorms and squalls called 'Kalbaisakhi' or Nor'westers. The metropolitan city Kolkata is getting 81.2 thunderstorms per year, with significance in the pre-monsoon season of 19.6 thunderstorms as per the climatological study by Tyagi (2007).

2.3. *Jharkhand*

The state is located in the eastern part of India and is also known as "The land of Forest" and is surrounded by the states like West Bengal in the east, Chhattisgarh in the west, Bihar in the north, Uttar Pradesh in the north-west and Odisha in the south. It covers an area of 79,710 km^2, with Ranchi as its capital city and Dumka as its sub-capital. The state's most areas lie in the Chota Nagpur plateau. Many rivers flow through this plateau, like Sankh, Barakar, North Koel, South Koel, Damodar, Subarnarekha and Brahmani. Jharkhand experiences the tropical dry and wet (Aw and As) climate in the south-east and Humid subtropical (Cfa) in the north (from Koppen's climate classification). It experiences summer, rain, autumn, winter and spring season. The temperature became high, and the summer from April 15 to June 15. The SW monsoon provides an annual rainfall of about 1000 mm in the west-central part and 1500 mm in the south-east regions of Jharkhand. Due to its topography and the presence of the Chota Nagpur plateau, it encounters thunderstorms whole over the state. From the thunderstorm climatology of Tyagi (2007), the capital city Ranchi experiences 73.4 thunderstorms per year, with 19.0 thunderstorms in the Pre-monsoon season.

3. Data description and methodology

In this study, we have utilised ECMWF re-analysis datasets (ERA-5) for the pre-monsoon season (March-May) for both 0000 (0530 local time) and 1200 UTC (1730 local time) over eastern India (Jharkhand, Odisha and West Bengal) from 1987-2016. ERA-5 is the latest and fifth generation of European re-analysis datasets

TABLE 1

Definition and references for the calculation of CAPE and CIN

Convective available potential energy(CAPE)	$\text{CAPE}\left(\text{J kg}^{-1}\right) = \int_{z_{\text{LFC}}}^{z_{\text{LNB}}} g\left(\frac{T_{\text{ve}} - T_{\text{vp}}}{T_{\text{vp}}}\right) dz$	Moncrief and Miller (1976)
Convective inhibition (CIN)	$\text{CIN}\left(\text{J kg}^{-1}\right) = \int_{z_{\text{bottom}}}^{z_{\text{top}}} g\left(\frac{T_{\text{v,parcel}} - T_{\text{v,env}}}{T_{\text{v,env}}}\right) dz$	Colby (1984)

produced by the European Centre for Medium-Range Weather Forecast (ECMWF) (Hersbach and Dee, 2016). ERA-5 data performs better than any other re-analysis products for evaluating the maximum/minimum temperature, precipitation, soil moisture and evapotranspiration over the Indian region (Mahto and Mishra, 2019). The air-sea flux estimation is also found to be better by ERA-5 data over the Indian region (Pokhrel *et al*., 2020). For the extreme rainfall estimation, the ERA-5 data sets are found to be better than other gridded satellite products (Bhattacharyya *et al*., 2022) but underestimate the rainfall categories compared to Indian Monsoon Data Assimilation and Analysis (IMDAA) (Singh *et al*., 2021). However, in the estimation of total runoff during monsoon season, climate forecast system re-analysis data performs better than ERA-5 (Mahto and Mishra, 2019). The ERA-5 data couldn't capture the precipitation patterns over the peninsular and hilly regions of India (Singh *et al*., 2021). The present study, however, doesn't account for the precipitation or total runoff values associated with pre-monsoon thunderstorms. Though ERA-5 has some limitations over the Indian region as any other re-analysis product, its fair estimate of various meteorological parameters over the gridded domain encourages us to use the product for the present study.

The thunderstorm event details were acquired from the India Meteorological Department, Pune (IMD Pune) and IMD Mausam Report over the diverse areas of study regions. In view of thunderstorm occurrence on a particular day or non-occurrence of the event (utilising IMD reports), we have classified the days as non-thunderstorm (NTD) and thunderstorm days (TD) (Tyagi and Satyanarayana, 2015).

For all the times of the study period, we computed CAPE and CIN from ERA-5 datasets. Table 1 represents the formulation used for the computation of CAPE and CIN (equations and references). The composite maps of thermodynamic indices (CAPE and CIN) have been developed for all the TD and NTD days of the study, for both 0000 and 1200 UTC.

Mann-Kendall test (MKT), a non-parametric statistical test for understanding trends in time-series datasets, has been used in the present work at the 95% confidence level ($p < 0.05$) (Asoka *et al*., 2017; Vissa *et al*., 2019). The MKT accepts the null hypothesis as the no monotonic pattern present in a time series, and the pattern values may be positive or negative. The trend values are obtained using Sen's slope (Sen, 1968).

4. Results and discussion

4.1. *Temperature and relative humidity variations over eastern India*

The temperature and humidity are two main drivers for the occurrence of any convective event (Braham, 1952; Weckworth, 2000). Strong convective instability with high moisture availability at lower levels, supported bya triggering/lifting mechanism, produces favourable conditions for thunderstorm development/occurrence over any region (Ghosh *et al*., 2004; Kessler, 1982). Therefore, understanding these two parameters over the study area is essential before analysing the CAPE and CIN variations. We have analysed the surface and upper-level temperature and humidity variations over Odisha, West-Bengal and Jharkhand to understand the role of these two parameters ininitiating the thunderstorms. The threshold values for relative humidity (RH) at 700 hPa level for different locations of eastern India for a 5-year interval period for both 0000 and 1200 UTC havebeen fixed by Sahu *et al*. (2020a). It was found that the RH threshold values are ~40-47 over Bhubaneswar, ~30-55 over Kolkata and ~34-58 over Ranchi (Sahu *et al*., 2020a).

It has been observed that for Odisha, the relative humidity (RH) at 1000 hPa for TD and NTD shows higher values over coastal districts extending to northern and southern districts. The difference is higher during the daytime (1200 UTC).

Though the RH values are a little higher during TD, the pattern of variation is similar in both cases. There is a remarkable difference for the RH value at the upper level

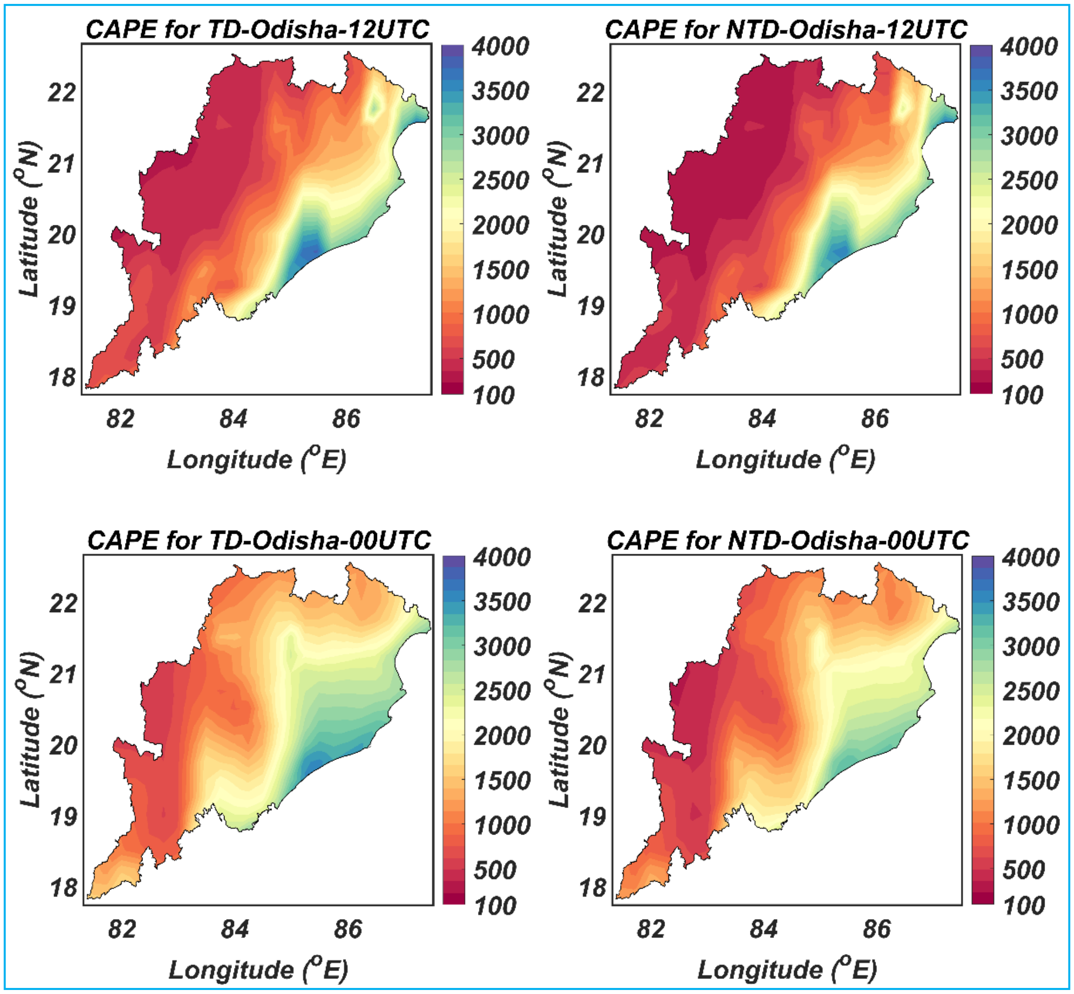

Fig. 2. Variation of CAPE for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Odisha. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

between 0000 and 1200 UTC, with higher RH values at 1000 hPa for 0000 UTC and higher RH values at 850, 700 and 500 hPa for 1200 UTC for both TD and NTD. The western districts of Odisha (bordering with Chhattisgarh) show moisture deficiency and a clear distinction between TD and NTD. The source of moisture over the area is the Bay of Bengal. As the humidity plays a crucial role in the development of thunderstorm cells at the surface and at mid-and upper levels, we have also analysed the variations of RH for 850, 700 and 500 hPa. The differences are significant for upper levels, with higher values for TD in all the levels and RH values approaching minimal at 500 hPa for NTD days (Supplementary Figs. S1 and S2). For the temperature variations, the analysis for 1000, 850, 700 and 500 hPa variations for TD and NTD (as for the RH variations) has been performed over Odisha (Supplementary Figs. S3 and S4). The 0000 UTC temperature variations show lower values to 1200 UTC as expected for all levels, with reduced values of temperatures as per moist adiabatic lapse rate for vertical variation in the atmosphere. The moisture availability during TD at all levels significantly lowers the temperature range compared to NTD. The coastal regions of Odisha, having higher RH values, are showing lower temperatures for both 0000 and 1200 UTC for both TD and NTD. The temperature variation patterns for TD and NTD shows higher ranges during NTD. Though the states show a difference between TD/NTD and 0000/1200 UTC, it is to be noted that for TD days (loaded with more moisture), the ranges are not very different to NTD, making the atmosphere conducive for occurrences of thunderstorm events on consecutive days (Sahu *et al.*, 2020a).

The RH variations over West Bengal are showing a different signature to that of Odisha due to the long

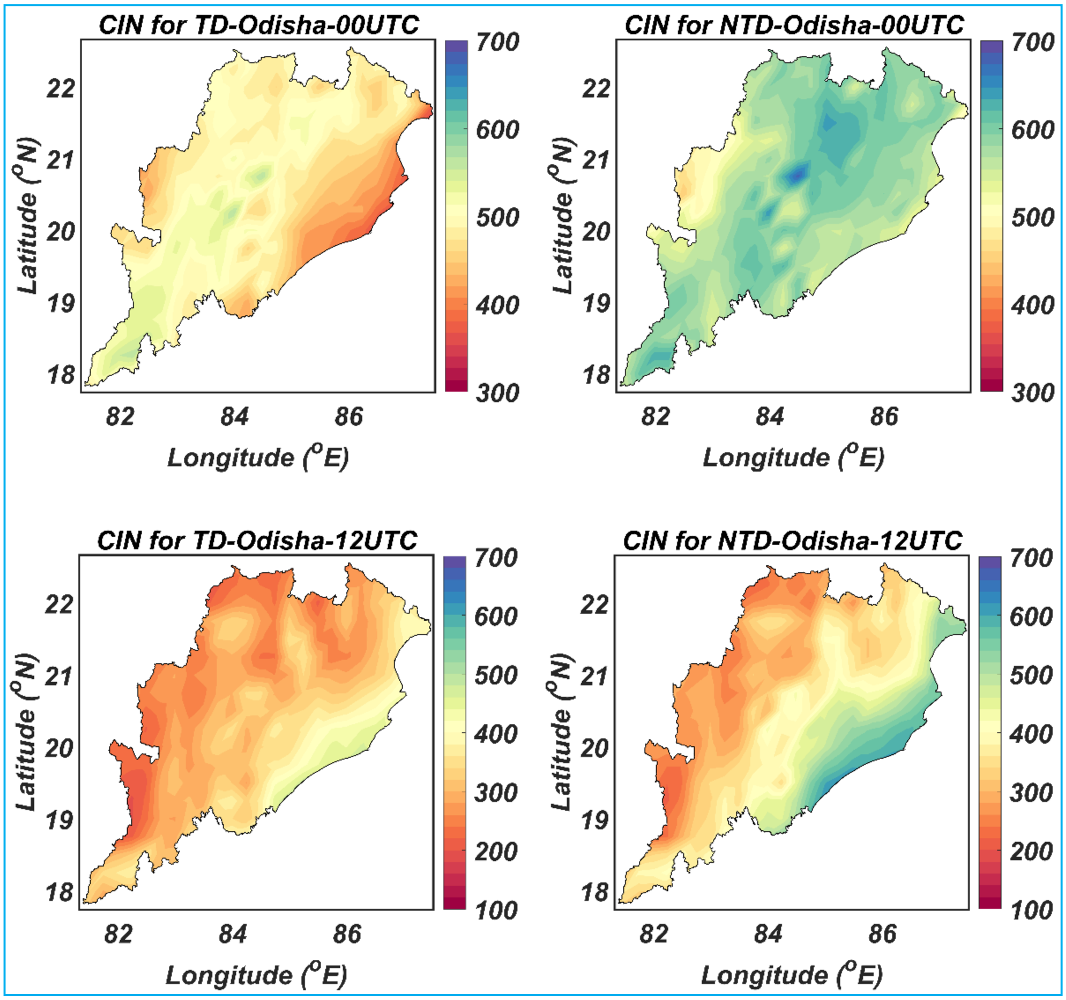

Fig. 3. Variation of CIN for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Odisha. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

coastline and close proximity to the Bay of Bengal, resulting in abundant moisture availability during the pre-monsoon season on a daily basis (Dalal *et al*., 2012). For the TD days, the 850 and 700 hPa humidity values are >50% for both 0000 and 1200 UTC, allowing the vigorous thunder cells to develop over the state. Though the NTD cases are showing relatively higher values of RH during 1200 UTC compare to 0000 UTC, there is a significant difference between TD and NTD humidity variations over the state, with higher values during TD. The mid-tropospheric values (500 hPa) also show higher values during the TD cases for both 0000 and 1200 UTC (Supplementary Figs. S5 and S6). Though the state of West Bengal has high RH values, the capital Kolkata and its nearby regions and northern districts (Siliguri, Cooch Behar, Darjeeling, Jalpaiguri etc.) are having higher RH values. As expected, the temperature values over West Bengal are relatively lower than Odisha due to higher humidity values for both 0000 and 1200 UTC. Though the temperatures are higher at 1200 UTC, they are in the ranges of 30-40°C over the state at 1000 hPa and the difference is less between TD and NTD (Supplementary Figs. S7 and S8).

The variations of RH and temperature over Jharkhand are more distinguishable between TD and NTD for both 0000 and 1200 UTC (Supplementary Figs. S9, S10, S11 and S12). The region receives transported moisture from the Bay of Bengal with enormous heating of the land during the pre-monsoon season. It lifts these warm air masses by the Chota-Nagpur plateau, creating a perfect environment for developing thundercells over the region (STORM Science plan, 2005). The 0000 UTC RH values are generally higher than the 1200 UTC values.

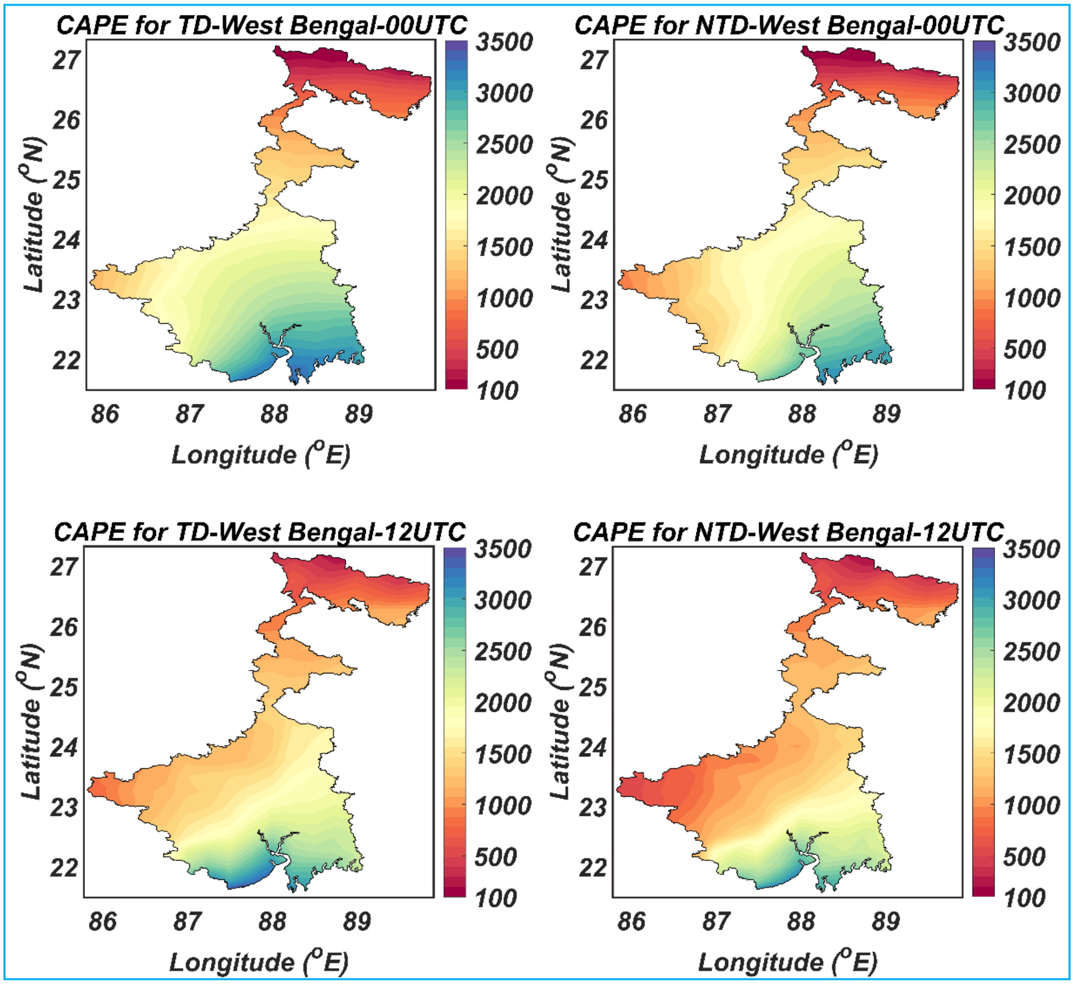

Fig. 4. Variation of CAPE for 0000 UTC (upper panel) and 1200 UTC (lower panel) over West Bengal. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

With the progression of the day, the increased heating of the plateau results in reducing the moisture availability in the atmosphere over the area (Tyagi and Satyanarayana, 2015). As observed over the West Bengal region, the differences are visible not only at 1000 hPa but also at 850 and 700 hPa between TD and NTD for both 0000 and 1200 UTC over Jharkhand. For Jharkhand, even the 500 hPa RH values can distinguish the TD/NTD difference for both 0000 and 1200 UTC. It is furthernoticed that though Jharkhand is not having a coastal district, the RH values for 0000 UTC TD follow the ranges observed over the states of West Bengal and Odisha. The temperatures are higher for both 0000 and 1200 UTC compared to Odisha and West Bengal (Supplementary Figs. S11 and S12). Though the 1200 UTC temperatures at 1000 hPa show slight differences, the ranges and spatial variation patterns are more or less the same for TD and NTD for both 0000 and 1200 UTC, leaving it to the availability of moisture content for producing the thunderstorm (Tyagi *et al*., 2012).

4.2. *Spatial variation of CAPE and CIN over Odisha*

To understand the spatial variation of CAPE and CIN over eastern India, we have prepared composite maps over the three states: Odisha, West Bengal and Jharkhand for the study period. The variability can be discussed further for each of the states concerning the information onthunderstorm occurrence. Fig. 2 shows the spatial variations of CAPE (for both 0000 and 1200 UTC) over Odisha for the average values of 1987-2016. The variation of CAPE for both 0000 and 1200 UTC over Odisha shows that coastal districts (south-eastern region of Odisha) show higher CAPE values for both TD and NTD. The variation is indicating a decrease in CAPE values as we move away

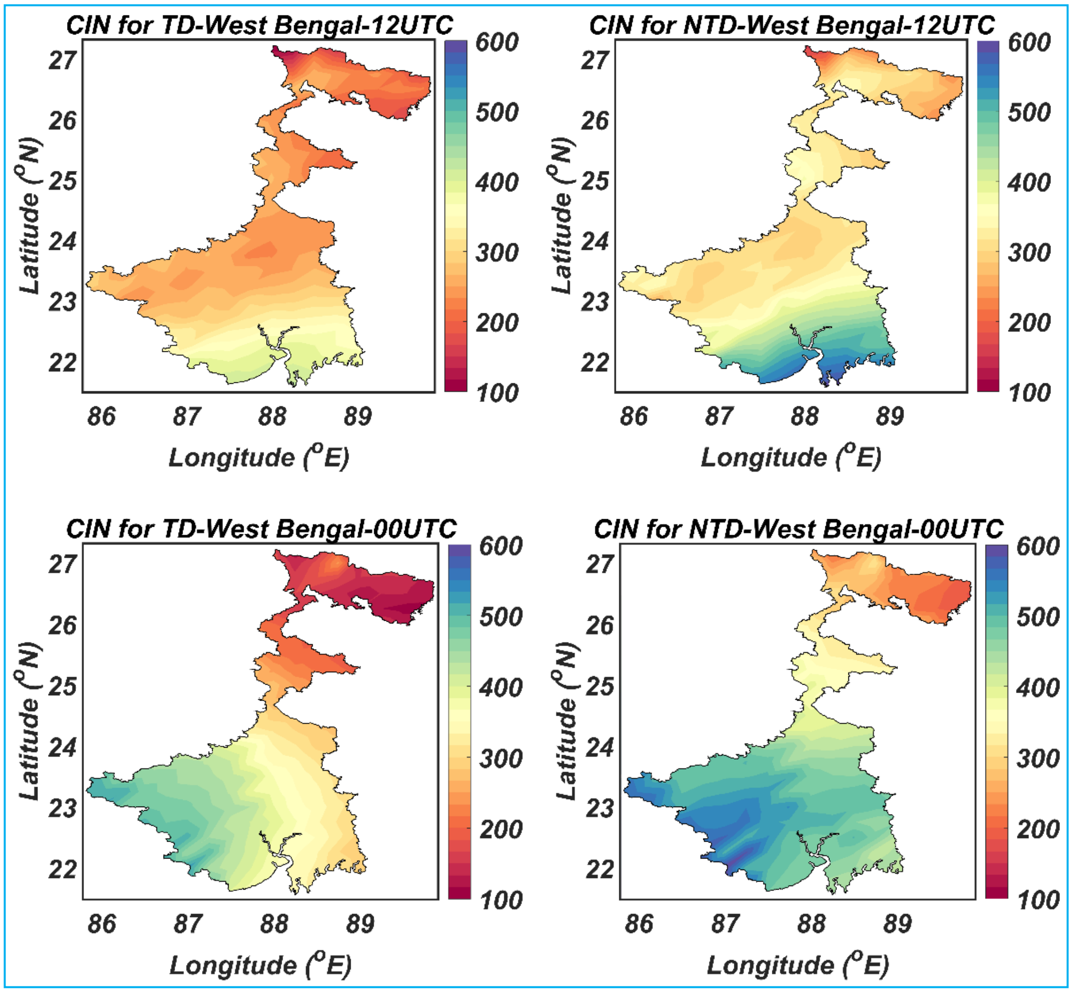

Fig. 5. Variation of CIN for 0000 UTC (upper panel) and 1200 UTC (lower panel) over West Bengal. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

from the Bay of Bengal. This higher CAPE variability over coastal districts supports the higher temperature and RH values over these regions, as discussed in the previous section, with higher CAPE values for TD than NTD for whole Odisha.

For 0000 UTC, during TD, CAPE values range from ≥700 to ≥3500 Jkg^{-1}, while during NTD, CAPE values range from≥500 to ≥3000 Jkg $^{-1}$. For 1200 UTC TD, CAPE varies from≥500 to ≥3800 Jkg $^{-1}$, while during NTD, CAPE ranges from ≥200 to ≥3500 Jkg $^{-1}$ over Odisha. As higher values of CAPE indicate a higher potential for a thunderstorm, Fig. 2 shows that the south-eastern part of Odisha, mainly coastal districts (Khurdha, Puri, Balasore, Bhadrak, Ganjam and Mayurbhanj district) is showing higher potential for thunderstorms during both 0000 and 1200 UTC, which is verified with the observations (Weather Reports, 2020). It is further noted that the higher CAPE values are extending for the state only over the coastal area. As the Odisha state borders Andhra Pradesh, the districts bordering the state over the land region show a reduced value of CAPE variations for both TD and NTD. Though the difference between TD and NTD is not very resilient, the CAPE for TD days over the region has higher values. The gradient is more prominent for western Odisha (bordering Chhattisgarh) for both 0000 and 1200 UTC. The west Odisha region also shows a significant decrease in CAPE values for 1200 UTC from 0000 UTC values for both TD and NTD, indicating the impact of less moisture availability over the region. The threshold values for thunderstorm occurrence over the area are ≥184 to ≥628 Jkg^{-1} for the 0000 UTC and ≥400 to ≥1790 Jkg^{-1} for 1200 UTC (Sahu *et al.*, 2020a). The coastal and central regions of Odisha are more conducive tothunderstorm occurrence.

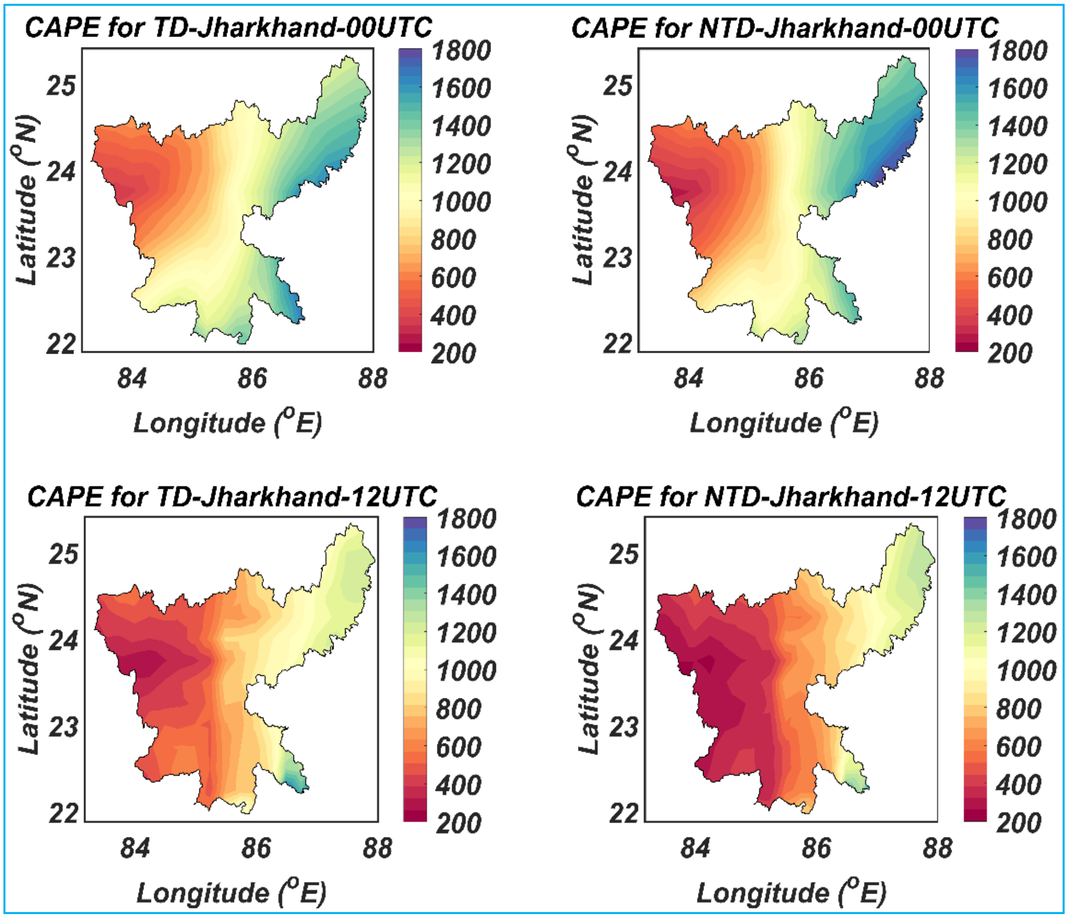

Fig. 6. Variation of CAPE for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Jharkhand. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

Apart from higher values of CAPE over any region, the requirement for initiation of the convective event is having low values of CIN (Tyagi *et al*., 2013b). The higher values of CIN indicate the lower potential for any convective activity development. Fig. 3 showsthe spatial variation of CIN for TD and NTD for 0000 and 1200 UTC over Odisha, respectively. NTD cases have higher CIN values over Odisha for both 0000 and 1200 UTC, inhibiting the development of any convective activity. The values for CIN are even higher in magnitude for 0000 UTC NTD comparedto 1200 UTC NTD over the region. For 0000 UTC, during TD, CIN ranges from ≥400 to ≥550 Jkg^{-1}, whereas for NTD, CIN ranges from ≥500 to ≥700 Jkg^{-1}. For 1200 UTC, during TD, CIN ranges from ≥200 to ≥500 Jkg^{-1}, whereas for NTD, CIN ranges from ≥250 to ≥700 Jkg^{-1}. The threshold values for CIN over the region for thunderstorm occurrence at 0000 UTC are ≥188 to ≥347 Jkg^{-1} and ≥174 to ≥216 Jkg^{-1} for 1200 UTC (Sahu *et al*., 2020a). Thus, the coastal region of Odisha fits in this criterion of both CAPE and CIN threshold for initiation of thunderstorm activity during 0000 UTC and central and western Odisha show a higher probability during 1200 UTC.

4.3. *Spatial Variation of CAPE and CIN over West Bengal*

The spatial variation of CAPE and CIN over West Bengal has been analysed for the study period during both 0000 and 1200 UTC. Fig. 4 shows the spatial variation of CAPE for 0000 and 1200 UTC over West Bengal.The CAPE values during TD are higher than NTD over West Bengal, except in the northern region (Jalpaiguri, Darjeeling, Cooch Behar, etc.).

For 0000 UTCTD, CAPE values range from ≥200 to ≥3500, while during NTD, CAPE values range from ≥200 to ≥3000. For 12 00 UTC TD, CAPE values vary from ≥500 to ≥3500, while during NTD, CAPE values range from ≥400 to ≥3000 over West Bengal. As the

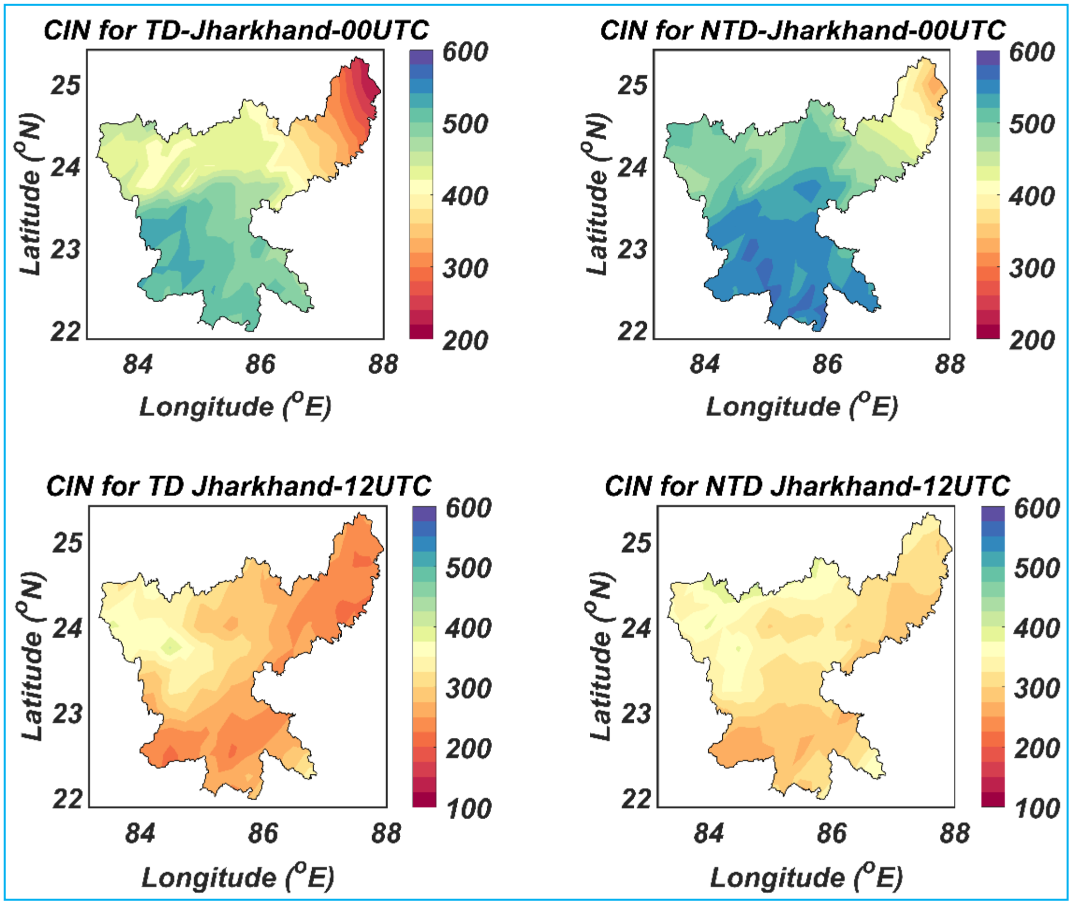

Fig. 7. Variation of CIN for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Jharkhand. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

greater extent of CAPE signifies a higher potential for a thunderstorm (Singh *et al.*, 2017); it can be observed that south-western parts of West Bengal are having a higher potential for thunderstorms during 0000 UTC compared with 1200 UTC. The observations support reporting an increase in night-time thunderstorm frequency over Kolkata in recent years (Weather report, 2020; Sahu *et al.*, 2020a). As observed for the Odisha, in West Bengal, the land-locked regions (northern West Bengal districts) have lower CAPE values than coastal districts.

The CIN values can differentiate the TD and NTD in a better way. Fig. 5 shows the CIN variations over West Bengal for 0000 and 1200 UTC for TD and NTD. Higher values of CIN persist over the state during NTD compared to TD during both 0000 and 1200 UTC; however, the 0000 UTC values have higher ranges. For 0000 UTCTD, CIN ranges from ≥100 to ≥450, whereas, for NTD, CIN ranges from ≥200 to ≥600. For 1200 UTC, during TD, CIN ranges from ≥200 to ≥400 and for NTD, ≥250 to ≥600. The higher CIN values during 0000 UTC act as acontrolling factor for thunderstorm occurrence over the region despite having higher CAPE values. The coastal districts show higher CIN values than the rest of the state districts and the magnitude of the values are higher during 1200 UTC. Unlike Odisha, where coastal districts showed high CAPE and low CIN values, the West Bengal coastal regions show higher values for both CAPE and CIN. Therefore, the thunderstorm occurrence over various parts of West Bengal should be understood as the availability of higher CAPE and low CIN values at the same time.

4.4. *Spatial variation of CAPE and CIN over Jharkhand*

Fig. 6 shows the spatial variation of CAPE over Jharkhand for both 0000 and 1200 UTC. The state shows an east-west gradient in CAPE values for both 0000 and 1200 UTC, with higher values towards the eastern side, bordering West Bengal. The values are not showing significant differences between TD and NTD over the region for 0000 UTC. However, during 1200 UTC, the

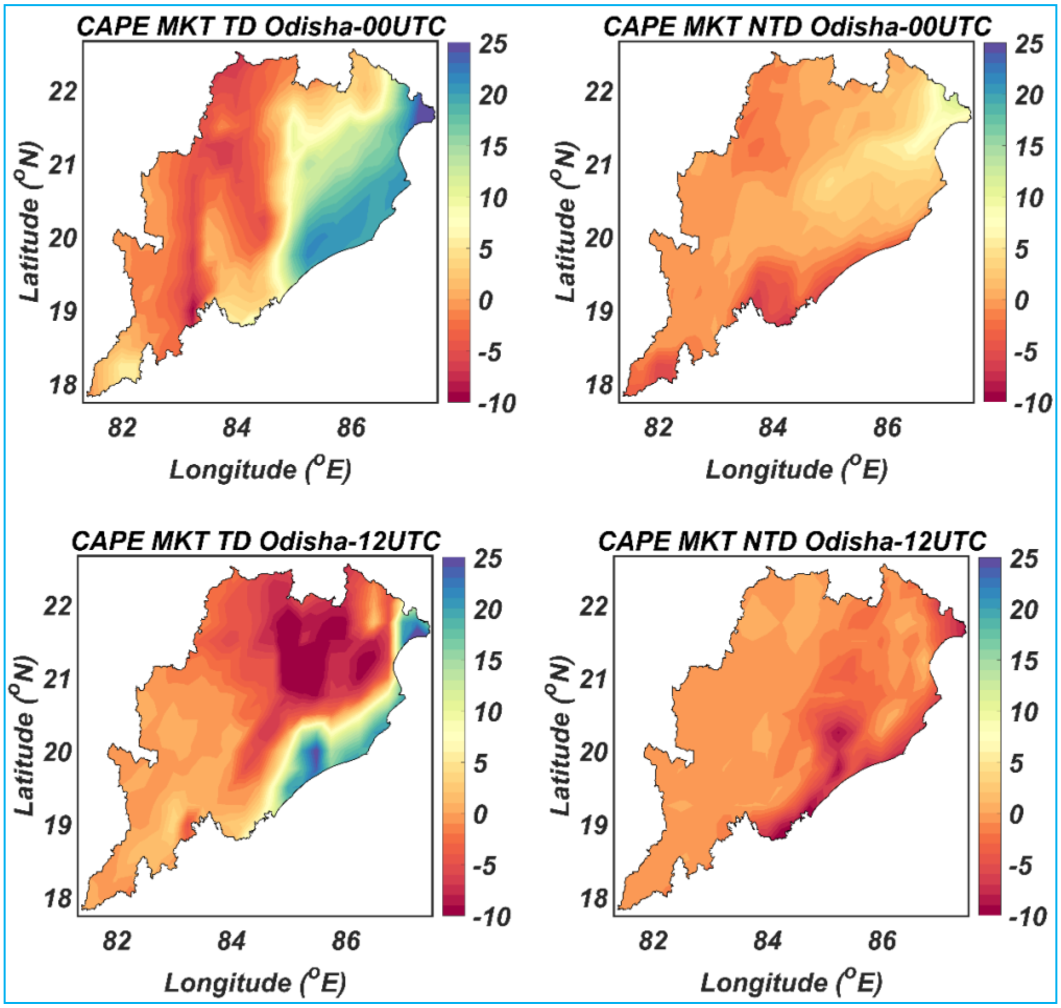

Fig. 8. Trend of CAPE for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Odisha. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

TD values are higher over the western part compared to NTD days. The higher CAPE values over the state suggest that higher heat availability over the state prevails for all the pre-monsoon days, as observed by Tyagi *et al.* (2013c). For 0000 UTC, during TD, CAPE ranges from ≥600 to ≥1800, while during NTD, CAPE ranges from ≥400 to ≥1800 and for 1200 UTC TD, CAPE varies from ≥400 to ≥1400, while during NTD, CAPE ranges from ≥200 to ≥1300 over Jharkhand.North-eastern and south-eastern regions of Jharkhand are having a higher potential for thunderstorms as these regions are showing higher CAPE values.

The CIN variability over Jharkhand is shown in Fig. 7. Unlike CAPE, the CIN can differentiate the TD and NTD for both 0000 and 1200 UTC. The CIN is not showing any gradient in the east-west like CAPE. For both 0000 and 1200 UTC, the CIN values are lower in TD cases compared to NTD. For 0000 UTC, during TD, CIN ranges from ≥200 to ≥500, whereas for NTD, CIN ranges from ≥350 to ≥600. For 1200 UTC, during TD, CIN ranges from ≥200 to ≥350 and for NTD, ≥250 to ≥450. The variation supports the fact that even higher values of CAPE exist for NTD cases; the higher values of CIN are preventing thunderstorms from occurring over the region, as observed by Tyagi and Satyanarayana (2015).

4.5. *Trends analysis for CAPE and CIN*

The trend analysis of CAPE and CIN indices over Odisha state has been performed to distinguish and classify the prevailing trends in their values and differences in the rate of change during different days (TD and NTD). Figs. 8 and 9 shows the trend variation of

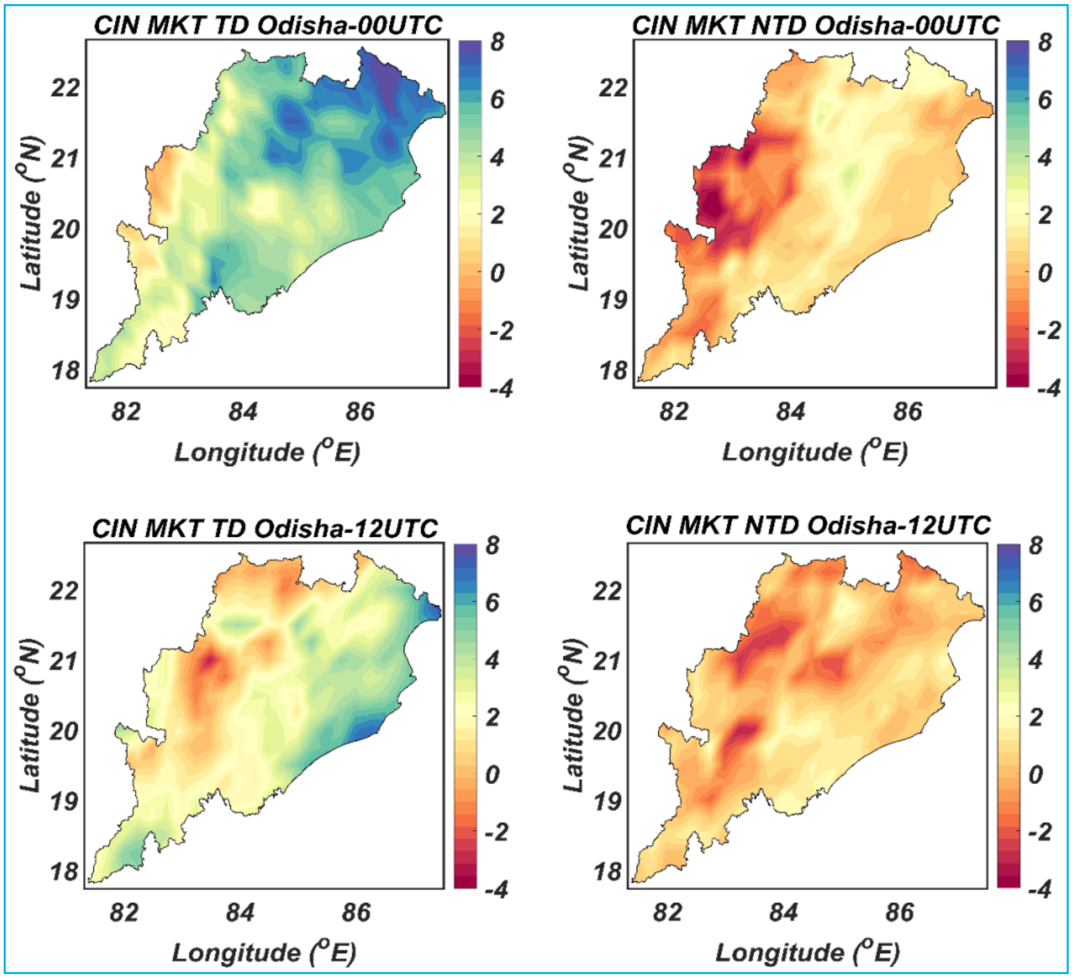

Fig. 9. Trend of CIN for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Odisha. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

CAPE and CIN for both 0000 and 1200 UTC over Odisha. The CAPE values show both increasing and decreasing trends over Odisha during 0000 and 1200 UTC (Fig. 8). The trend is positive for the coastal region of Odisha (*i.e.*, Balasore, Bhadrak and Mayurbhanj district), more distinctively appearing for TD. The spatial extent of the positive trend region is more significant in 0000 UTC for TD compared to 1200 UTC. In contrast, the 0000 UTC of NTD only shows an increasing trend in CAPE values for the coastal region of Odisha. The negative trends in CAPE values are observed in central, north and east-coast of Odisha districts like Gajapati, Ganjam, Puri, Khurdha, Kendujhar, and Dhenkanal. In the case of TD, for 1200 UTC, Ganjam, Puri, Jagatsinghpur, Kendrapara, Bhadrak and Balasore districts are having high trend values (~25 J/kg per season/year). Kendujhar, Mayurbhanj, Dhenkanal, Cuttack, and Nayagarh are showing high negative trend values (~ ─5 to ─10 J/kg per season/year). Similarly, for 0000 UTC, during TD, most parts of the state show positive trend values from 5 to 25 J/kg per season/year with high positive values over Ganjam, Puri, Khurdha, Jagatsinghpur, Kendrapara, Bhadrak and Balasore districts. Koraput, Malkangiri, Nabarangpur, Kalahandi, Balangir, Nuapada, Baragarh and Sambalpur districts shows a negative trend from ─5 to ─10 J/kg per season/year.

Fig. 9 shows trend variations for CIN (0000 and 1200 UTC) over the study region. The positive trend for CIN is observed over northern Odisha (~6-8 J/kg per season/year) during 0000 UTC TD, whereas during 0000 UTC NTD, this value decreased to ~2 J/kg per season/year. The CIN trend during 1200 UTC is decreasing over north-western parts of Odisha (Sundargarh, Bargarh, Balangir and Nuapada) during both TD (~ –2 J/kg per season/year) and NTD (~ –4 J/kg perseason/year).

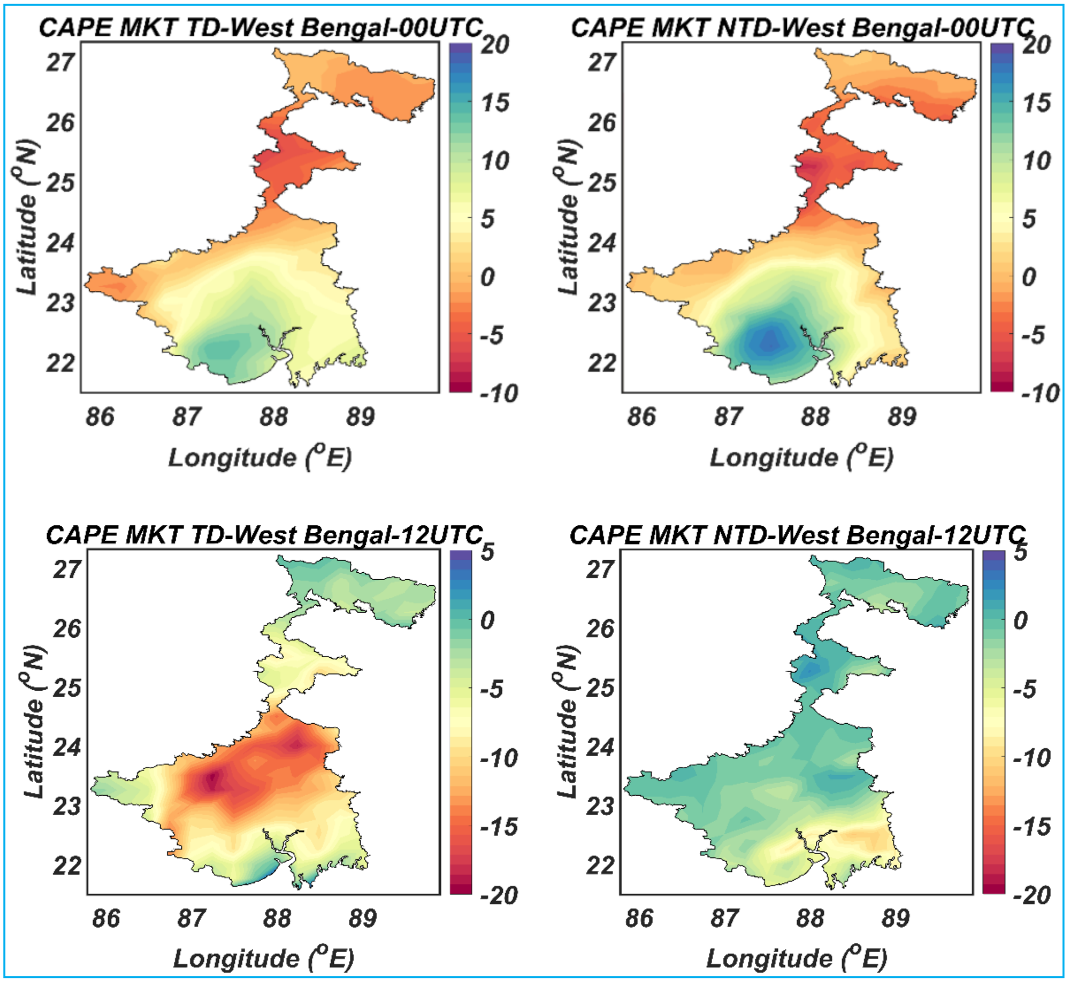

Fig. 10. Trend of CAPE for 0000 UTC (upper panel) and 1200 UTC (lower panel) over West Bengal. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

However, the coastal districts show opposite trends in TD and NTD, increasing trends of ~4-6 J/kg per season/year during TD and ~ –2 J/kg per season/year during NTD. The results show that daytime (1200 UTC) decreasing CIN values are assisting the probability of increasing thunderstorms, while night-time increasing trends support the decreasing thunderstorms over the region (Sahu *et al.*, 2020). Examining these trends simultaneously with CAPE trend values, the outcomes are signifying that the east coast of Odisha region (Khurdha, Kendrapara, Ganjam, Bhadrak, Jagatsinghpur, Puri, Balasore), the values are changing drastically and is a suitable region for thunderstorm occurrence during both day and night time with the changing climate.

Figs. 10 and 11 shows the trend variation of CAPE and CIN for 0000 and 1200 UTC over West Bengal. The CAPE trends show that for 0000 UTC, except for northern parts of West Bengal (*i.e.*, Siliguri, Jalpaiguri, Darjeeling, Cooch Behar, etc.), there are positive trends in TD and NTD (Fig. 10). The southern districts (*i.e.*, Howrah, West Medinipur, East Medinipur, Haldia) have higher positive trends during 0000 UTC. The northern districts of West Bengal are showing a negative trend during 0000 UTC. During 1200 UTC, there is a shift from negative to positive trend values for northern districts and during TD, the state is showing a decreasing trend of CAPE. The trend is increasing during NTD for 1200 UTC. For 0000 UTC TD days, the CIN shows a positive trend for the region, with western parts showing a higher trend (Bankura, Purulia, Raniganj etc.). For 1200 UTC CAPE,the NTD showsa positive trend (~1 to 5 J/kg per season/year) for most of the state. However, North 24 Parganas, South 24 Pargana, Howrah, Purbo and Pashchim Medinipur districts show a slight negative trend (~ –1 to –10 J/kg per season/year). During TD, it shows

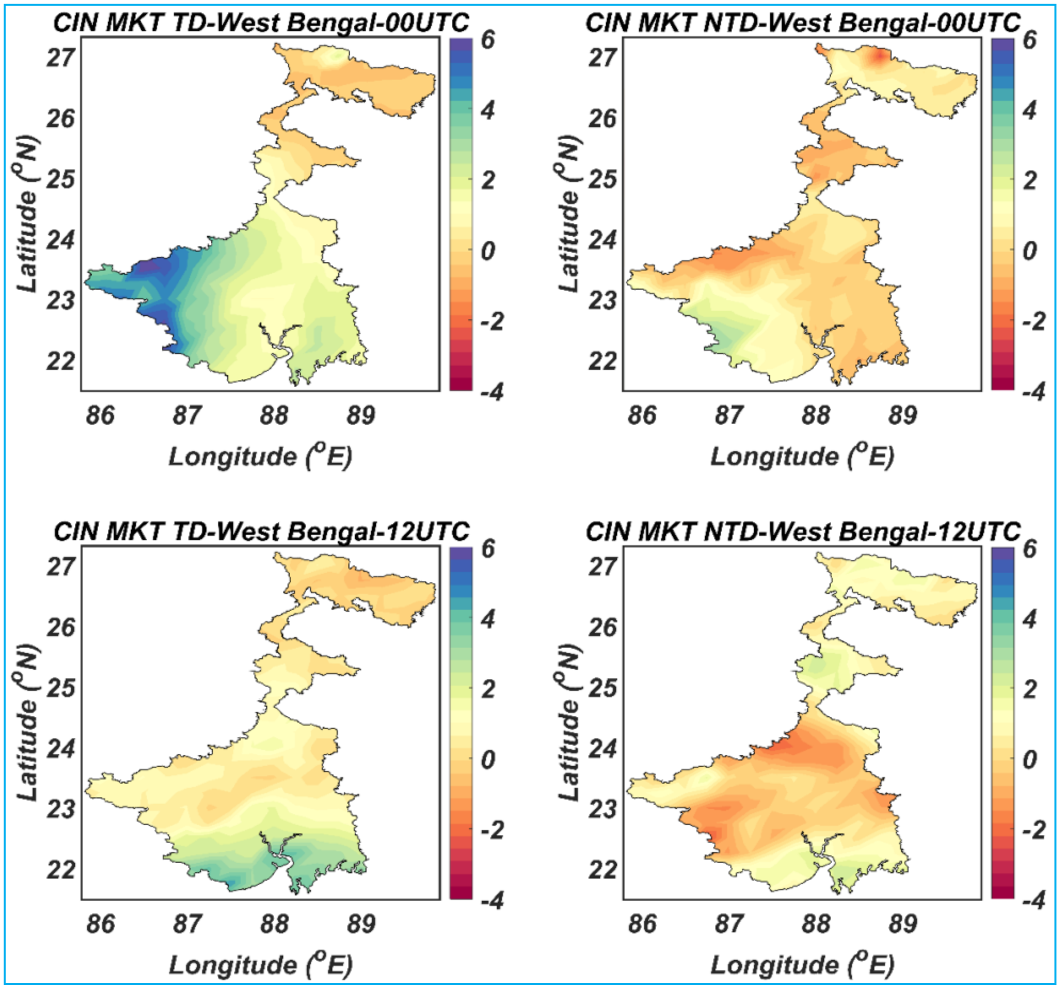

Fig. 11. Trend of CIN for 0000 UTC (upper panel) and 1200 UTC (lower panel) over West Bengal. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

the decreasing trend over the whole state, with northern West Bengal districts (*i.e.*, Darjeeling, Kalimpong, Jalpaiguri, Cooch Behar and Alipurduar) showing increasing trend values (~1 to 5 J/kg per season/year).

For both 0000 and 1200 UTC NTD, the CIN showsa decreasing trend in several districts of West Bengal (Fig. 11). For 0000 UTC, the CIN values in the TD areshowing an increasing trend for most of the state (~1 to 6 J/kg per season/year). Northern districts show a slightly negative trend and the values range from ~0 to -2 J/kg per season/year. For NTD CIN values, most of the parts in West Bengal are showing a slightly negative trend (~0 to -4 J/kg per season/year). Some districts (*e.g.*, Jhargram, Purba and Pashchim Medinipur, Bankura, Murshidabad, Darjeeling and Cooch Behar districts) show a slightly positive trend (~0 to 2 J/kg per season/year). For 1200 UTC TD, CIN values mostly showa positive trend, ranging from ~0 to 6 J/kg per season/year. During NTD, CIN trend values are slightly increasing/decreasing, ranging from ~ –2 to +2 J/kg per season/year. The increasing trends are visible for 1200 UTC of TD and NTD for southern districts (*i.e*., Howrah, West Medinipur, East Medinipur, Haldia). The increasing trends in CIN values can differentiate the TD and NTD for both 0000 and 1200 UTC over West Bengal. However, the region is not showing a strong gradient in increasing/decreasing trend values between coastal and landlocked districts as that of Odisha.

Fig. 12 shows that for 0000 UTC TD days, the CAPE shows a negative trend in most parts of Jharkhand, with some districts in the western region (*e.g.*, Palamu, Latehar, Garhwa, Lohardaga, Gumla and Khunti) showing

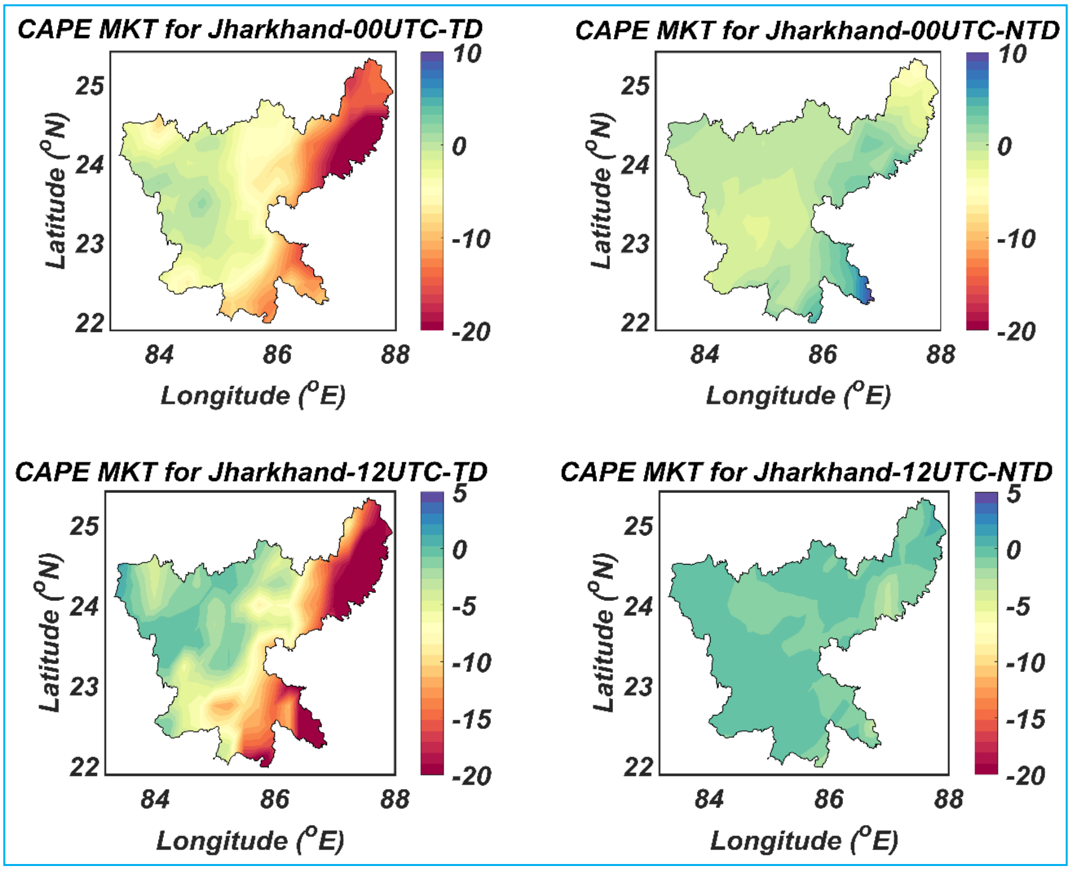

Fig. 12. Trend of CAPE for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Jharkhand. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

a slightly positive trend and the values are ranging from (~ –20 to 2 J/kg per season/year). The CAPE trends during1200 UTC are positive for all the districts except the ones bordering West Bengal and Odisha, with the values ranging from ~ –5 to 5 J/kg per season/year. During NTD, the CAPE shows increasing trends for both 0000 and 1200 UTC, with higher values during 1200 UTC. Fig. 13 depicts trends of CIN for 0000 and 1200 UTC over Jharkhand. For 0000 UTC TD, except few districts in western Jharkhand (Latehar, Garhwa and Palamu), there is an overall decreasing trend in CIN values. For 0000 UTC NTD over Jharkhand, CIN is showing an increasing trend over the whole region, except the districts of Garhwa and Palamu and the trend values are in the range of ~ –1 to 7 J/kg per season/year. Similarly, for 1200 UTC TD, CIN shows decreasing trend values over the state, except few districts with a positive trend (Latehar, Saraikela Kharsawan and East Singhbhum). For 1200 UTC NTD, CIN values show a negative trend over the Jharkhand region with small patches of a positive trend over the areas of Khunti, Gumla, Ranchi and Giridih districts.

5. Summary and conclusion

This paper discussed the CAPE and CIN climatologies for pre-monsoon thunderstorm season over Eastern India using ERA-5 re-analysis data from 1987 to 2016. The CAPE and CIN climatologies proved to be useful globally for understanding convective development (Potter and Anaya, 2015; Meukaleuni *et al*., 2016; Chen *et al*., 2020; Taszarek *et al*., 2021). Based on ERA-40 re-analysis data, Riemann-Campe *et al*. (2009) has developed global CAPE and CIN climatology from 1958-2001. The results attributed trends in CAPE values to specific humidity, as moisture plays a vital role in CAPE determination (Haines, 1989). The Indian region showed positive trends in Riemann-Campe *et al*. (2009), as observed in the present study. Pre-monsoon season is categorised by intense thunderstorm activity over India, with severe events over eastern and north-eastern India.

The frequency and intensity of thunderstorm occurrence over the study region provide an idea about the destructive and recurring nature of the events, which is

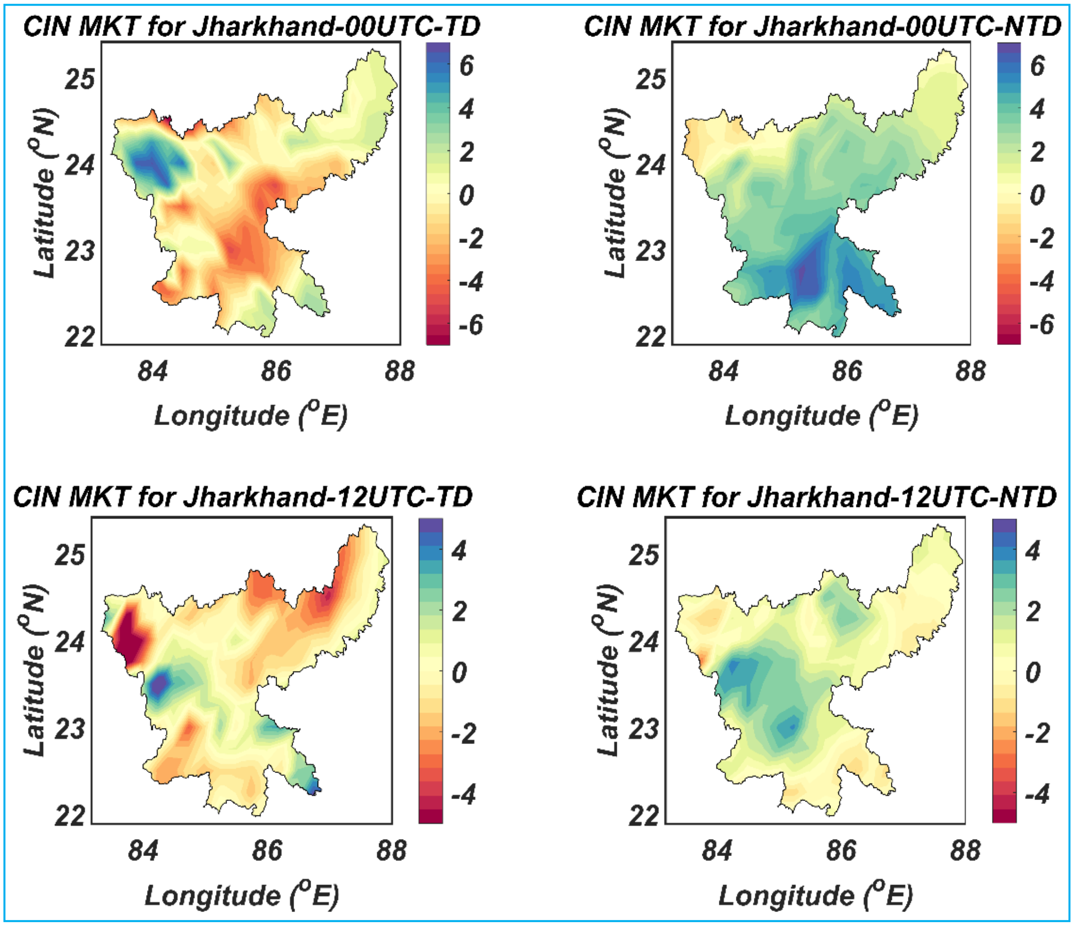

Fig. 13. Trend of CIN for 0000 UTC (upper panel) and 1200 UTC (lower panel) over Jharkhand. The left side panel shows the variations for TD, whereas the right-side panel shows NTD variations

essential to plan for safety measures. In a previous study, Tyagi (2007) has reported the seasonal climatology of thunderstorms over India and the mean number of thunderstorm days observed over Kolkata, Kalaikunda, Bhubaneswar and Ranchi were 19.6, 30.6, 17.7 and 19, respectively, for the pre-monsoon season. We found similar thunderstorm frequencies over the eastern and northern parts of Odisha, northern and southern parts of West Bengal and southern and central parts of Jharkhand. For comparing these particular sites based on Tyagi (2007), during thunderstorm days, the CAPE trend for Kolkata is increasing from (~10 to 15 J/kg per season/year), while the 1200 UTC trend is slightly negative (~ –5 to –10 J/kg per season/year). The CIN trend is positive for both 0000 UTC and 1200 UTC (~0 to 2 J/kg per season/year). Over Bhubaneswar, the CAPE trend reveals a greater positive tendency for both 0000 UTC and 1200 UTC (~20 to 25 J/kg per season/year), while the CIN values also show a slightly positive trend from (~4 to 6 J/kg per season/year). Similarly, for Ranchi, the CAPE values indicate a minor positive/negative trend for 0000 UTC and 1200 UTC (~ –5 to 5 J/kg per season/year), while the CIN trend shows a slight negative trend value for both 0000 UTC and 1200 UTC (~0 to –4 J/kg per season/year for 0000 UTC and ~0 to -2 J/kg per season/year for 1200 UTC).CAPE trends in Kalaikunda are positive (~10 to 15 J/kg per season/year) in 0000 UTC and somewhat negative in 1200 UTC (~ –5 to –10 J/kg per season/year), whereas CIN trends are positive in both 0000 UTC and 1200 UTC (varying from ~2 to 4 J/kg per season/year).

The CAPE and CIN values vary substantially in our study area. Over Kolkata on thunderstorm days, CAPE values range from ≥2500 to ≥3000 J/kg and CIN values range from ≥350 to ≥400 J/kg. At 0000 UTC and 1200 UTC, CAPE values range from ≥2000 to ≥2500 J/kg and CIN values range from 250 to 350 J/kg. Over Bhubaneswar, CAPE values on thunderstorm days range from ≥3000 to ≥3500 J/kg for both 0000 UTC and 1200

UTC, while CIN values range from ≥400 to ≥500 J/kg for 0000 UTC and ≥350 to ≥450 J/kg for 1200 UTC. CAPE values in Ranchi vary from ≥800 to ≥1200 J/kg for 0000 UTC and ≥800 to ≥1000 J/kg for 1200 UTC, with CIN values ranging from ≥450 to ≥550 J/kg for 0000 UTC and ≥250 to ≥350 J/kg for 1200 UTC. Similarly, CAPE values in Kalaikunda are increasing, ranging from ≥3000 to ≥3500 J/kg for 0000 UTC and ≥2700 to ≥3200 J/kg for 1200 UTC, whereas CIN values range from ≥350 to ≥450 J/kg in 0000 UTC and ≥300 to ≥400 J/kg in 1200 UTC. It is to be noted that over eastern India, most of the thunderstorms (70.2 %) occurs with CIN values in ranges of 0-150 J/kg and only 1% of thunderstorms occur with CIN values >450 J/kg. However, in these 70.2% of thunderstorms, the CAPE values are widely distributed to percentage of thunderstorm occurrence: 12.9% with 0-1000 J/kg, 20.2% with 1000-2000 J/kg, 17.7% with 2000-3000 J/kg and 19.4% with >3000 J/kg (Chaudhuri, 2011). The vertical growth of the convective weather system may not be accurately represented by CAPE/CIN, as both fat CAPE and skinny cape may lead to thunderstorm events by keeping the same value (https://www.meted.ucar. edu/index.php). For our work, though the CAPE values range from low to high, we attempted to understand the vertical growth byplotting the CAPE/CIN values on Skew-T log P diagrams, with marked areas of CAPE and CIN. For our work, we have selected ~50 thunderstorm cases over eastern India to plot the CAPE/CIN values and respective vertical areas on Skew-T log P diagrams. Based on our understanding with the help of analysed data, we may say that the CAPE values associated with the different ranges 0-1000 J/kg are having in general vertical growth of convective system up to 11,000 m, whereas the ranges 1000-2000 J/kg are having vertical growth up to 11,000-13,500 m, ranges 2000-3000 J/kg are having vertical growth up to 14,000 m andconvective systems with >3000 J/kg CAPE values reach up to a height of >14000 m. As reported in the literature (Sen Roy *et al*., 2021), with the threshold valuesof CAPE over eastern India, the false alarm ratio (FAR) is low (0.21-0.40) and the probability ofdetection (POD) is high (0.61-1.00). However, these favourable values still have a chance to miss out on the occurrence of the event. Thus, statistically, the chances tomiss the thunderstorm with sufficient CAPE is 21-40 % after having sufficient CAPE values over the eastern region. The non-occurrence of thunderstorm with sufficient CAPE values is not systematic, as they depend on other environmental conditions, *e.g*., CIN values, and moisture availability over the region (Tyagi *et al*., 2013c).

The results are crucial for understanding long term climatological changes in the convective environment over eastern and north-eastern India during the pre-monsoon season. We looked at the regional differences in CAPE and CIN values and their trends from 1987 to 2016. The findings of the present study can be concluded as follows:

(*i*) The CAPE values are having a sharp gradient between coastal and inland regions over Odisha. The values are higher for coastal stations and decreasing as we are going towards inland districts. The difference between TD and NTD are not very prominent over Odisha. However, the CIN values show distinguishable differences between TD and NTD for both 0000 and 1200 UTC. The CIN values are lower over coastal districts during TD cases, indicating low inhibition, making a conducive environment for thunderstorm activities.

(*ii*) The CAPE trends are positive over coastal districts of Odisha during TD cases of 0000 and 1200 UTC but change to negative trends as we move to inland districts. The CAPE trends are negative for both 0000 and 1200 UTC during NTD cases over Odisha. Complimenting to CAPE trends, the CIN trends are also negative for both 0000 and 1200 UTC during NTD cases. However, positive CIN trends are observed during TD cases, especially over coastal districts with higher values during 0000 UTC. The trends are suggesting that coastal districts are having high chances of increased TD activities.

(*iii*) West Bengal shows higher CAPE values for both 0000 and 1200 UTC during TD and NTD. However, the gradient is high as observed for Odisha and the values range from 100 to 3500 J/kg over the region. The TD cases are showing relatively higher values of CAPE, with 0000 UTC showing greater values. CIN values demark the TD and NTD cases with higher CIN values during NTD for both 0000 and 1200 UTC. The results proposea conducive environment for thunderstorm occurrence over the coastal region of West Bengal, revealing the reason for higher frequencies of thunderstorm occurrences in the region.

(*iv*) The CAPE trends are similar for TD and NTD during 0000 UTC, with positive trends over coastal West Bengal and negative trends innorthern districts. However, during the 1200 UTC, there are negative trends values during TD cases, whereas the NTD shows positive trends. CIN values show positive trends during TD (0000 UTC) with higher values for districts bordering Jharkhand, whereas the positive trends are limited to only coastal districts during TD for 1200 UTC. The NTD cases are showing negative trends of CIN for both 0000 and 1200 UTC. The results advocate increasing thunderstorm potential for night-time/early morning over West Bengal compared to daytime.

(*v*) The CAPE values are relatively lower in Jharkhand compared to West Bengal and Odisha but follow a gradient pattern from one side of the state to another. Here the districts sharing the boundary with Odisha and West Bengal states are having higher CAPE values. The difference between 0000 UTC TD and NTD CAPE values is not very significant; however, during 1200 UTC, there are some lower values during NTD cases over a large part of the state. CIN values can differentiate TD and NTD cases for both 0000 and 1200 UTC. Higher CIN values during NTD cases approve thunderstorm occurrences during TD cases over Jharkhand.

(*vi*) The trends are opposite to the values range for CAPE over Jharkhand. The districts bordering West Bengal and Jharkhand show negative CAPE trends during TD cases (for both 0000 and 1200 UTC), with positive trends moving to western side districts. The CAPE trends are positive for the whole Jharkhand for NTD cases, though the values are high during 0000 UTC. The CIN shows negative trends for almost the entire state during TD cases (except a few places showing positive trends), whereas the CIN trends are positive during NTD. The results are indicating that the future may have more intense thunderstorm occurrences over the state.

The results are providing a basis for understanding pre-monsoon convective activities over eastern India. However, further analysis with recent years inclusion may improve the variability and may further strengthen the results. The present study's future application will be to aid forecasters in developing climatological maps throughout several Indian states to comprehend the spatial variation of thermodynamic indices, which will aid in identifying the location of convective occurrences and to provide early warning to the public.

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