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Evaluation of thermodynamics of the atmosphere in relation to pre-monsoon convective activity over north India

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सार – इस शोध पत्र में मानसून ऋतु के पूर्व के महीनों के दौरान उत्तर भारत में वायुमंडल की उर्ध्वधर संरचना और गहन संवहन (वृष्टि) की परिवर्तनशीलता के परस्पर संबंध का अन्वेषण वर्ष 2001 के आँकड़ों का उपयोग करते हुए किया गया है। पूर्वी भारत का प्रतिनिधित्व करने वाले कोलकाता और उत्तरी पश्चिमी भारत का प्रतिनिधित्व करने वाले दिल्ली के लिए निदर्श विश्लेषण क्षेत्र के केप और अन्य तापगतिकीय प्राचलों का परिकलन किया गया है। इन दो स्टेशनों के उर्ध्वधर भ्रमिलता निष्पादन का भी आकलन किया गया है। इस अध्ययन में कोलकाता और दिल्ली दोनों में वर्षा की राशि के साथ केप के क्षीण सहसबंध का पता चलता है। किन्तु फिर भी आशाजनक परिणाम यह रहे हैं कि बाद के दिन में संवहनी सक्रियता की घटना अथवा घटना के न घटने को समझने के लिए इसमें उपयुक्त अच्छे स्किल स्कोर (वायस और थ्रेट स्कोर) हैं। वायुमंडल की उर्ध्वधर संरचना के समय के विकास से यह ज्ञात होता है कि मानसून ऋतु के आगे बढ़ने के समय कोलकाता में संवहनी सक्रियताओं की प्रकृति में परिवर्तन आता है। निम्न क्षोभमंडलीय भ्रमिलता पर वर्षा और अधिक निर्भर हो जाती है तथा गहन संवहन के लिए आद्रता वाली स्थितियाँ संचाालित होने लगती हे और निम्न क्षेाभमंडलीय भ्रमिलता में महत्वपूर्ण वृद्धि के कारण मानसून वर्षा ऋतु के आगे बढ़ने के साथ–साथ ऊँचे संवहनी मेघ बनने लगते हैं। मानसून पूर्व ऋतु के सिनॉप्टिक पैटर्नों के कारण संवहनी वर्षा के गतिकीय सहयोग के सुदृढ़ीकरण से ऋतु की प्रगति के साथ–साथ ये और सुस्पष्ट होने लगते हैं। दिल्ली में मानसून वर्षा ऋतु के आरंभ में वर्षा आद्रता पर अधिक निर्भर करती है। इस मामले में कोलकाता में जैसे जैसे निम्न क्षोभमंडलीय भ्रमिलता वाले क्षेत्र में वर्षा की बढती हुई निर्भरता के साथ–साथ ऋतु की प्रगति होती जाती है वैसे वैसे संवहन की प्रकृति में भी परिवर्तन आता जाता है। तथापि दिल्ली में गतिकीय सहयोग के संवहन महत्वपूर्ण प्रवृतक नहीं है। इस अध्ययन से यह तथ्य भी सामने आता है कि कोलकाता में निम्न स्तर में दिन के प्रति दिन वायुमंड़ल में शुष्कता ऊपरी सतह में शुष्क हवा के कमी के कारण होती है। जबकि दिल्ली में क्षैतिजीय अभिवहन मुख्यतः वायुमंड़ल की आद्रता की मात्रा में परिवर्तन के लिए उत्तरदायी है।

ABSTRACT. This paper explores the relationship between the vertical structure of the atmosphere and variation of deep (precipitating) convection over north India during pre-monsoon months using data for the year 2001. From the model analysis field, CAPE and other thermodynamic parameters for Kolkata, as representative of east India and Delhi, as representative of northwest India, are computed. The vertical vorticity profiles for these two stations have also been calculated. The study reveals that both for Kolkata and Delhi CAPE is poorly correlated with the rainfall amount. However, the encouraging result is that it has reasonably good skill score (bias and threat scores) to explain occurrence or non-occurrence of convective activity on the subsequent day. Time evolution of vertical structure of atmosphere indicates that nature of convective activities over Kolkata changes as the season advances. The rainfall becomes more dependent on lower tropospheric vorticity and moisture conditions become conducive for deeper convection and taller convective clouds to form with the advance of the season due to a significant increase in the lower tropospheric vorticity. This strengthening of the dynamic support to convective rainfall may be because of the pre-monsoon synoptic pattern becoming more pronounced with the progress of the season. Over Delhi, rainfall dependence on moisture is more at the beginning of the season. As for Kolkata, in this case also character of convection changes as season progresses, with increasing dependence of rainfall on lower tropospheric vorticity field. However, dynamic support is not an important initiator of convection over Delhi. The study also suggests that, the day to day drying of the atmosphere in the lower levels over Kolkata is due to subsidence of upper layer dry air while over Delhi, horizontal advection is mainly responsible for the change in moisture content of the atmosphere.

Key words – Convective activity, CAPE, CINE, Equivalent potential temperature, Vorticity

1. Introduction

Southwest monsoon sets over India around the first week of June. However, the build up of energy, moisture and different dynamical parameters start much before the monsoon season. An important mechanism by which thermodynamic changes take place over India during the pre-monsoon season is through convective activity.

Therefore, a study of the thermodynamics of the atmosphere during pre-monsoon season provides a window of opportunity for understanding the monsoon processes. Pre-monsoon season over India extending from March to May is characterized by very good convective activity all over the country. Convective activity progressively increases from March onwards as the season advances. Though thunderstorm activity may continue over the country even during the monsoon season, the severity of thunderstorms is marked only in the pre-monsoon season, when they, on a number of occasions, are accompanied by squalls and hails. (Srinivasan *et al*., 1973).

East India, is one of the regions in India with high incidence of thunderstorm activity. In the region of Gangetic West Bengal, majority of the thunderstorms is in the afternoon (Rao and Boothalingam, 1957). These thunderstorms generally develop over Bihar plateau and adjoining areas and subsequently move in a southeasterly direction. Climatologically, in this region, it has been observed that, as the lower tropospheric moisture increases, the chance of thunderstorm activity also increases. Moisture supply in the lower troposphere boundary layer is provided by the shallow layer of southerlies and southwesterlies from the anticyclonic cell over the Bay of Bengal (Srinivasan *et al*., 1973). Convective activity in this region is known as "Nor'wester" or "Kalbaisakhi".

Northwest India, is a region where a heat low develops gradually as the early summer season progresses. The heat low is very shallow and no associated upper air cyclonic circulation is observed. Spells of convective activity are due to the passage of western disturbances or its associated lows over Pakistan, northwest India and adjoining areas or due to boundary layer moisture supplies from the anticyclone over Arabian Sea. In general, convective activity in this region is called duststorm or "Aandhi".

Due to the contrasting nature of the synoptic conditions over the two regions, the two stations - (a) Kolkata as representative of east Indian weather conditions and (b) Delhi as representative of northwest Indian weather conditions, have been selected in this study for computation and analysis of various thermodynamic and dynamic processes in relation to the convective activities.

It has long been realized that deep convection requires the troposphere to be convectively unstable for the ascent of a moist parcel through a relatively deep layer. A particularly useful measure of the energy available for convection in the tropical atmosphere is Convective Available Potential Energy (CAPE). CAPE provides a measure of the maximum possible kinetic energy that an unstable parcel can acquire assuming that parcel ascends without mixing with the environment and instantaneously adjusts to the local environmental pressure (Srivastava and Sinha Ray, 1999). CAPE has been shown to play an important role in mesoscale convective systems (Moncrieff and Miller,1976) and (Dutta and De., 1999).

Studies of McBride and Frank (1999), Thompson *et al*. (1979) and Bhat *et al*. (1996) and Williams and Renno (1993) also demonstrated the role of CAPE in tropical atmosphere. However, no study exists to correlate the daily values of CAPE with those of convective activities over Indian region during the pre-monsoon season.

The goals of this study are:

(*i*) To determine the relationship between CAPE (for air originating at the surface) and convective activities and

(*ii*) Evolution of vertical structure of atmosphere with reference to deep convection.

Our interest is to investigate the local environment conditions that cause the rain producing mesoscale systems. The diagnostic understanding of such a phenomenon will be of much help in the future development of forecast models for predicting local rainfall.

2. Data

In the present study, data for the pre-monsoon season of 2001 for the period from 15 March to 31 May is considered. The primary data used are from the daily analysis fields (at resolution of $1° \times 1°$ Lat./Long.) of India Meteorological Department's operational forecasting system known as Limited area Analysis and Forecasting System (LAFS). The LAFS is a complete system consisting of real time processing of data received on the Global Telecommunication System (GTS), decoding and quality control procedure handled by AMIGAS software, 3-D multivariate optimum interpolation scheme for objective analysis and multilayer primitive equation model. The first guess field for running the analysis scheme is obtained from the global forecast (T 80) of the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi. To derive the parameters for the stations Kolkata and Delhi, corresponding nearest grid point data are considered. Rainfall data for the two stations on any day is the 24 hours total rainfall for a day as reported on 0300 UTC of the next day.

3. Methodology

According to the parcel theory, CAPE is a measure of the energy realized when conditional instability is released. Only surface values of CAPE have been used in analyses, as it has been observed in the Gulf of Carpentria during the AMEX experiment, that air parcels raised from above 900 hPa in the deep tropics rarely become positively buoyant (McBride and Frank, 1999). Following the method described by Williams and Renno (1993),

$$\text{CAPE} = -\int_{P_{\text{LFC}}}^{P_{\text{LNB}}} \left(T_{vp} - T_{ve}\right).Rd\,.\text{d}\left(\ln P\right)$$

where P_{LFC} : is the pressure level of free convection for parcel raised from 1000 hPa level

P_{LNB} : is the pressure level of neutral buoyancy for parcel raised from 1000hPa level

T_{ve} : is the virtual temperature of the environment at pressure level P through which parcel rises

T_{vp} : is the virtual temperature of the parcel at pressure level P through which parcel rises

Rd : is the dry gas constant

In cases when P_{LNB} was not found, the above integral was extended from P_{LFC} to 200 hPa (Dutta and De, 1999). Condensation, precipitation, freezing of liquid water and level of parcel origin, influence the virtual temperature of the air parcel and hence CAPE, as the parcel undergoes undiluted ascent in the atmosphere (Emanuel, 1994).

Several procedures have been suggested for evaluating CAPE depending on certain thermodynamic and microphysical assumptions. However, it has been demonstrated that, for a deep cloud, in which icing/glaciation takes place, estimated CAPE is almost independent of microphysical processes within the cloud and a pseudoadiabatic process will be sufficient to estimate CAPE (Williams and Renno, 1993). Also, cloud tops calculated by pseudoadiabatic process are closer to observation and for such processes uncertainties in evaluating CAPE values due to measurement errors are negligible compared to CAPE values (Fu *et al*., 1994). Hence, in this case, CAPE is evaluated assuming the pseudoadiabatic process of parcel ascent.

As a possible barrier to the initiation of conditional instability in the presence of high CAPE values, Williams and Renno considered a parameter - the Convective Inhibition Energy (CINE) (Williams and Renno, 1993). CINE, from the same data set, is evaluated as follows,

$$\text{CINE} = -\int_{P_{\text{SFC}}}^{P_{\text{LFC}}} \left(T_{vp} - T_{ve}\right).Rd\ \ .\text{d}\left(1\text{n}P\right)$$

where P_{SFC} : is the surface pressure level *i.e*. 1000 hPa.

Computational steps of CAPE and CINE are as follows.

(*i*) From the 1000 hPa values of temperature and moisture, the Lifting Condensation Level (LCL) of a surface parcel is calculated, presuming the conservation of dry static energy.

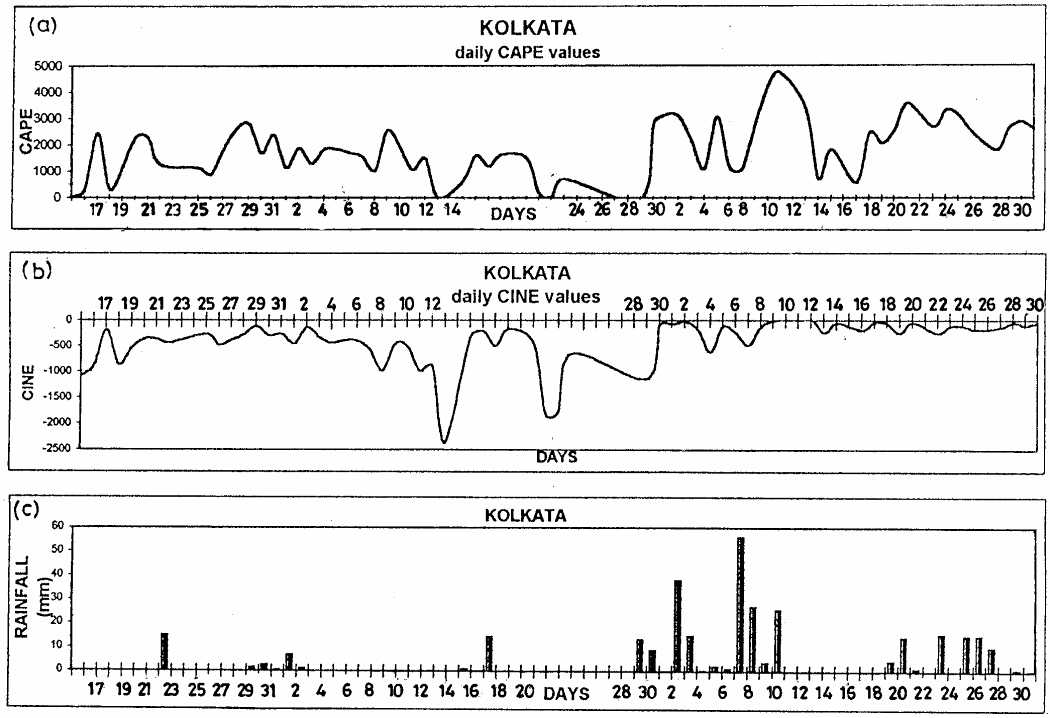
(*ii*) For the vertical integration purpose the environment vertical profile of temperature and moisture were interpolated and smoothened at 10 hPa intervals using the Cubic Spline Technique.

(*iii*) Above the LCL pressure level, the moist adiabat values of the parcel temperature and moisture were calculated for the 1000 hPa parcel. This was calculated at 10 hPa intervals, presuming the conservation of moist static energy.

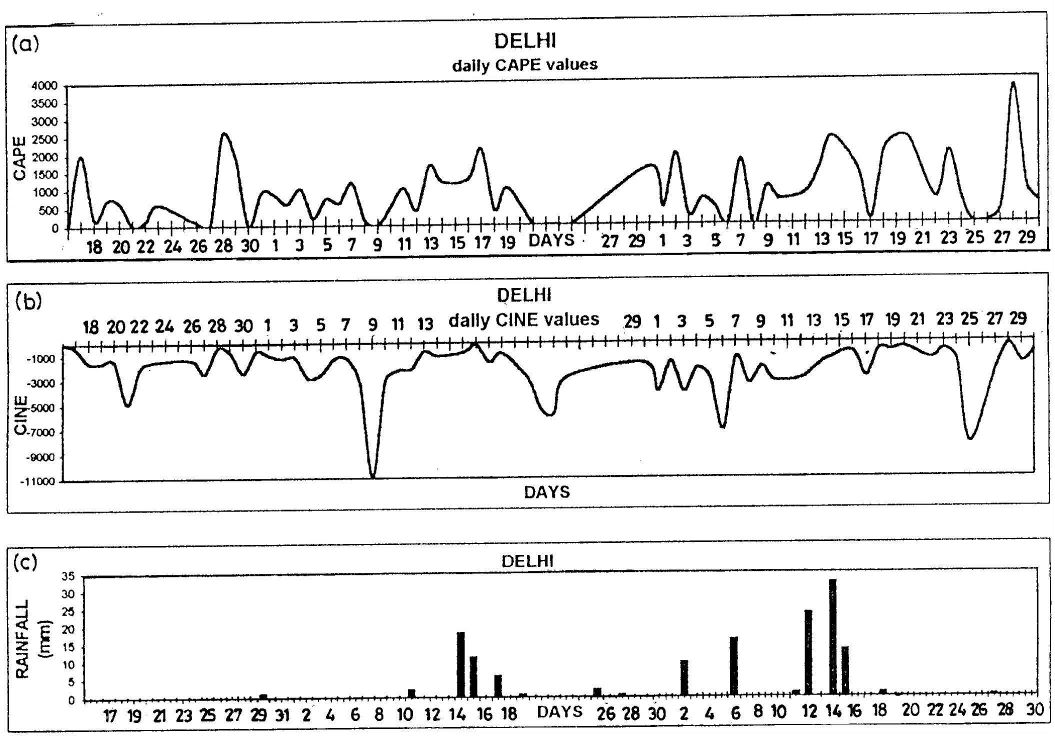
(*vi*) Using the two sets of values of temperature and moisture, the parcel P_{LFC} and P_{LNB} pressure levels were calculated.

(*v*) Then, the above integrands calculated at 10 hPa intervals and summed over – from P_{LFC} to P_{LNB} to calculate CAPE and from P_{SFC} to P_{LFC} for calculating CINE.

The original vertical resolution of the model analysis field consists of 14 pressure levels, *i.e*., 1000 hPa, 925 hPa, 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300hPa, 250 hPa, 200 hPa, 150 hPa, 100 hPa, 70 hPa and 50 hPa. In the present study, we used the analysis field based on 1200 UTC observation only. Initially, we attempted to compute thermodynamical parameters based on RS/RW observations. But later, it was realised that on many occasions CAPE/CINE could not be computed due to non-availability of 200 hPa (P_{LNB}) sounding data.



Figs. 1(a-c). (a) For Kolkata, day to day variation of CAPE(J/kg) values for the period from 15 March to 30 May, 2001, (b) for Kolkata, day to day variation of CINE(J/kg) values for the period from 15 March to 30 May, 2001, (c) same as Fig. 1(a) except for 24 hours observed rainfall (mm)



Figs 2(a-c). Same as Figs. 1(a-c) but for Delhi

4. Results and Discussion

Figs. 1(a&b) represents the daily variation of CAPE and CINE respectively for Kolkata from 15 March to 31 May 2001. A few days on which 1200 UTC data could not be downloaded due to computer problem are excluded. Figs. 2(a&b), similarly, represents the daily variation of CAPE and CINE respectively for Delhi for the same period. Fig. 1(c) and Fig. 2(c) represents the daily rainfall for the same period over Kolkata and Delhi respectively.

According to the definition, CAPE is calculated for the air parcel when it ascends beyond the P_{LFC} and CINE is calculated for the same air parcel rising from surface (1000 hPa) to P_{LFC} . This implies that when P_{LFC} is not obtained, value of CAPE becomes zero and CINE becomes arbitrarily large(negative). As such large negative values of CINE do not make any sense, these may be ignored in Figs. 1(a&b) and Figs. 2(a&b).

As the season progresses, the winter synoptic pattern is replaced by the pre-monsoon synoptic pattern. Consequently, the dependence of convective activity on the various parameters changes. To bring out the evolution of the convective activity, the season has been arbitrarily divided into two parts - from 15 March to 22 April and from 23 April to 31 May. Correlation coefficient (CC) between rainfall with the thermodynamic and dynamic parameters has been calculated separately for each half of the season to bring out the evolution of the nature of the convective activity.

4.1. *CAPE in relation to convective activity*

Table 1 represents the correlation coefficient (CC) of CAPE with the rainfall amount for Kolkata and Delhi, for each half of the season. As it is evident from the Table that for Kolkata, CC of CAPE with rainfall amount in the first half of the season is poor (CC = –0.03). This correlation improves in the second half of the season (CC = 0.152) but is, nevertheless not very good. For Delhi, the CC in the first half of the season is 0.08 and improves slightly to 0.14 as the season advances.

Weak negative correlation between rainfall and different thermodynamic parameters like CAPE in the tropics during Australian monsoon season around the Gulf of Carpentria was previously reported by McBride and Frank (1999) and Thompson *et al*. (1979). A high positive value of CAPE alone, without a triggering mechanism in the form of a synoptic system, can induce convective activity in the atmosphere in the vicinity of the station, if value of Convective Inhibition Energy (CINE) is less. However, for tropical regions, it has been observed that inhibition energy (CINE) of the order of 20 J/kg is strong

TABLE 1

Correlation coefficient of CAPE at station with 24 hours rainfall for the first and second half of the season

CAPE at station	Rainfall of first half	Rainfall of second half
Kolkata	-0.03	0.15
Delhi	0.09	0.14

TABLE 2

For Kolkata skill scores of CAPE (using threshold value as 1089 J/kg) with subsequent day's occurrence of rainfall activity

Station name : Kolkata	Bias score	Threat score
CAPE Threshold value 1089 J/kg	1.3	0.70

enough to act as a barrier to vertical updrafts from surface reaching the P_{LFC} and beyond (Williams and Renno,1993). In case of Kolkata as well as Delhi, on all days, even with high values of CAPE, values of CINE are very high, as in Figs. 1(a&b) and Figs. 2(a&b). This may be one reason, for the lack of very strong correlation over Kolkata as well as Delhi between CAPE and rainfall amount over the station. Dynamic field is essential for realization of thunderstorm activity at station.

According to the studies of Bhat *et al*. (1996), high positive correlation was observed between CAPE and the frequency of the occurrence of Highly Reflecting Cloud cover (HRC), a measure of convection in the tropical regions. Encouraging results are obtained when one attempts to correlate the frequency of occurrence of convective activity at station as indicated by days of rainfall rather than its amount with the value of CAPE of the previous day. Bias and threat skill scores (Stanski *et al*., 1989) calculated for CAPE with reference to subsequent occurrence of convective activities are shown in Table 2. Using a threshold value for CAPE as 1089 J/kg (the minimum value associated with occurrence of rainfall on the subsequent day), it is observed that CAPE has reasonably good skill scores (bias = 1.3 and threat = 0.70) to predict the occurrence/non-occurrence of thunderstorm activity over Kolkata.

Unlike for Kolkata, where majority of thunderstorms occurs in the afternoon (Rao and Boothalingam,1957), the rainfall over Delhi is not confined to any particular time of the day. Since the tropical atmosphere does not reveal any signature of impending convective activity, 6-12 hours in

TABLE 3

For Delhi skill scores of occurrence of convective activity on the subsequent day with CAPE (using threshold value as 207 J/kg) and with 24 hours change (rise) in the value of CAPE (using threshold value as 521 J/kg)

Station Name : Delhi	Bias score	Threat score
CAPE Threshold value 207 J/kg	3.3	0.3
CAPE rise Threshold value 521 J/kg	1.26	0.72

TABLE 4

Correlation coefficient of CAPE with equivalent potential temperature and specific humidity of 1000 hPa

CAPE at station	θ_e (surface)	Q (surface)
Kolkata	0.839	0.843
Delhi	0.729	0.85

advance (Roy, 1950), to investigate the role of CAPE in prediction of convective activity over the station, a time window of three hours just before and after 1200UTC observation has been selected. Thunderstorm activity over the station, with or without rainfall has been related to the value of CAPE of the previous day. The dry subcloud layer air in the tropical region prevents rainfall from reaching the ground. Due to the comparative dryness of mid troposphere over a continental station like Delhi, thunderstorm activity does not necessarily result in rainfall unlike Kolkata. The resultant threat and bias scores as indicated in Table 3 for a threshold value of 207 J/kg (the minimum value associated with occurrence of convective activity on the subsequent day), are not very encouraging. However, interestingly, when the parameter for predicting the convective activity is considered as the 24 hour change (rise) in the value of CAPE on the day prior to the occurrence of thunderstorm activity, results for a threshold value of 521J/kg (the minimum value associated with occurrence of convective activity on the subsequent day) are encouraging (bias = 1.26 and threat = 0.72). This is justified because thunderstorm activity is generally preceded by rise in the convective energy in the atmosphere as quantified by CAPE.

4.2. *Vertical structure of atmosphere in relation to deep convection*

Previous studies have shown a very strong dependence of the parameter $CAPE_{surface}$, on the surface

TABLE 5

Correlation of 24 hours rainfall at Kolkata with specific humidity and vorticity of different levels for the first half and second half of the season

Rainfall at Kolkata	Q (first half)	Q (second half)	Vorticity (first half)	Vorticity (second half)
1000 hPa	0.09	0.19	–0.08	0.55
950 hPa	0.05	0.04	–0.12	0.56
850 hPa	0.03	–0.03	–0.25	0.43
500 hPa	0.34	0.06	–0.23	–0.34

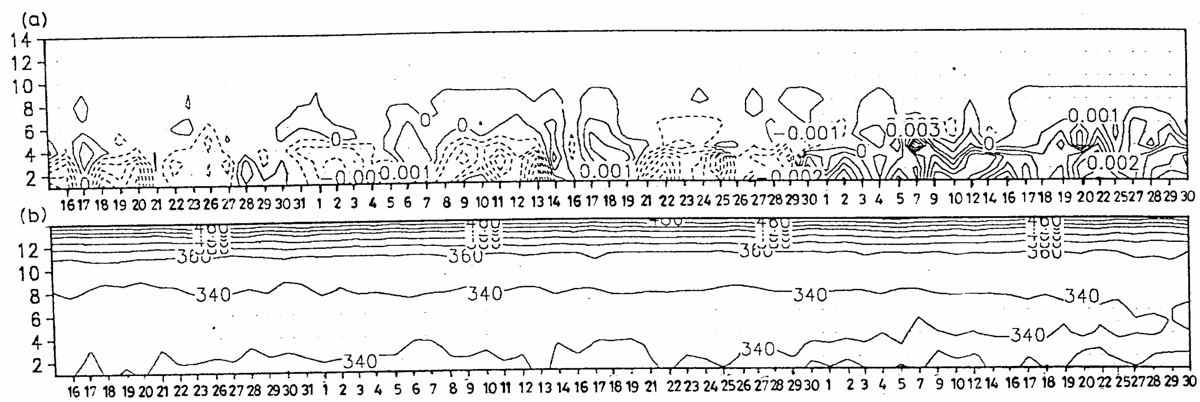
TABLE 6

Correlation of 24 hours at Delhi with moisture and vorticity of different levels for the first half and second half of the season

Rainfall at Delhi	Q (first half)	Q (second half)	Vorticity (first half)	Vorticity (second half)
1000 hPa	0.19	0.07	0.04	0.21
950 hPa	0.23	0.03	0.04	0.21
850 hPa	0.26	–0.02	0.04	0.15
500 hPa	0.13	0.09	0.16	–0.12

moisture as well as the surface equivalent potential temperature (McBride and Frank, 1999). Table 4 lists the correlation of the parameter CAPE with the 1000 hPa values of moisture as quantified by the specific humidity (Q) and equivalent potential temperature (θ_e) of 1000 hPa for the whole season. As it is evident, a strong correlation does exist between CAPE, as also, with equivalent potential temperature. Mathematically, this seems to be due to the fact that, boundary layer θ_e values determine whether there will be positively buoyant air in the first place and which actual moist adiabat will the rising parcel follow.

To quantify the dependence of rainfall on the vertical thermodynamic profile of the atmosphere over Kolkata, Table 5 represents the correlation coefficient of rainfall with moisture (specific humidity Q) and vorticity of different pressure levels. It is observed from the Table that, over Kolkata for the first half of the season, rainfall is more closely related to mid tropospheric (500hPa) moisture (CC = 0.34) than to surface moisture field (CC = 0.09). In addition, during the initial part of the season, a negative mid tropospheric (500 hPa) vorticity field appears to favour rainfall (CC= –0.23). However, as the season progresses, the dependence of rainfall on



Figs. 3(a&b). (a) Vertical profile of specific humidity (gm/gm) field departures from the level mean over Kolkata, for the period 15 April to 30 May,2001. Vertical levels 1-14 indicate pressure levels (hPa) 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200,150, 100, 70 and 50 respectively and (b) Same as Fig.3(a) except for equivalent potential temperature (°K) field

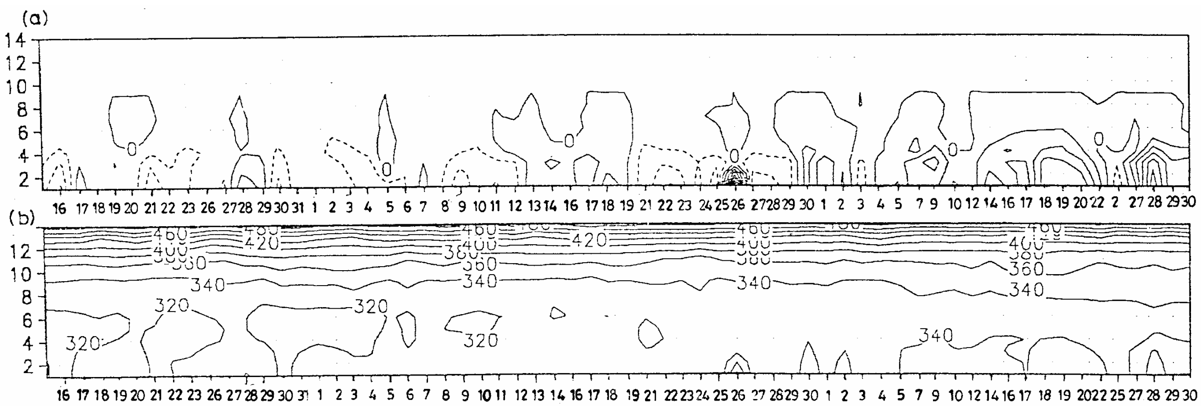
various parameters changes. In the latter half of the pre-monsoon season, correlation of rainfall to surface moisture slightly increases (CC = 0.19) and to mid tropospheric moisture decreases.

It is interesting to note that the CC of rainfall with low level positive vorticity field becomes considerably higher (CC = 0.55) in the later half of the season. According to the statistics documented by Peterssen (1956), deep convection is mostly associated with cyclonic vorticity (750 hPa), while anticyclonic vorticity supports shallow convection. Though the data refers to middle latitudes, his conclusions appear to be applicable to the tropics as well (Srinivasan *et al.*, 1973). This leads to the hypothesis that the character of the rainfall causing clouds changes as the season advances. Initially the clouds are shallow cumuli, with moisture supply mainly in the middle troposphere from synoptic systems in association with western disturbances. As the season advances, the Bay of Bengal anticyclone strengthens, moisture supply in the boundary layer increases due to prevailing southerlies and south-easterlies and the cumulus clouds formed are taller and result in good rainfall activity. The stronger dependence of rainfall on dynamic parameters (vorticity) as the season advances, signifies that rainfall is more often associated with some low level circulation over this region during the latter part of the season.

For Delhi in the first half of the season, rainfall shows a positive correlation (Table 6) with the lower tropospheric moisture content (CC = 0.19). This year, the anticyclonic cell over Arabian Sea may have played an important role to provide boundary layer moisture during the initial part of the season. The above finding supports the observation. However, as the season advances, rainfall is very poorly correlated with the moisture content of any level. In the first half of the season, the CC of rainfall with positive vorticity field improves with height - from 0.04 at 1000 hPa to 0.21 at 500 hPa. As the season advances, dependence of rainfall on lower tropospheric positive vorticity field increases (CC = 0.21) while the correlation with mid tropospheric vorticity field becomes weakly negative (CC = –0.12). This increased dependence of rainfall on the lower tropospheric positive vorticity field as the season advances reveals that the convection deepens as the season progresses. However, poorer correlation of rainfall to the vorticity field as compared to Kolkata implies that the dynamic field is not an important initiator of rainfall activity at the station. Lack of association between low level vorticity and rainfall activity over Delhi may be due to poor moisture supply over the region.

In an effort to better understand the rainfall over the station, the vertical thermodynamic profile of the atmosphere over the station has been studied. Fig. 3 represents the vertical profile of the atmosphere over Kolkata for the period 15 March to 31 May, 2001.

Increase or decrease of the value of CAPE on a daily basis may be due to the fact that it is primarily dependent on the moisture content of the corresponding level of parcel origin (McBride and Frank, 1999). Deep convection requires moisture influx through a relatively deep layer and is sometimes suppressed by influx of dry midlevel air into areas that were previously convectively active. Hence, analysis of the vertical profile of moisture content of the atmosphere is essential to understand not



Figs. 4(a&b). Same as Figs. 3(a&b) but over Delhi

only the reason for the daily variation of CAPE but also of rainfall. To examine the behaviour of the vertical structure of moisture in the atmosphere with reference to convection, the deviations of specific humidity from the level mean for this data period have been plotted in Fig. 3(a). In the beginning of the season, days of rainfall are in general associated with moisture increase in the mid troposphere. As the season advances, the increase in moisture vis a vis the convective activity is more in the lower troposphere as compared to the middle troposphere. Also, on correlating with the daily rainfall data, the inferences of Table 5 are confirmed.

Atmospheric drying occurs primarily through horizontal advection or subsidence and the cause is best interpreted from study of the vertical profile of the equivalent potential temperature. To determine which process is responsible, we examine profiles of the relevant conserved quantity, equivalent potential temperature θ_e in Fig. 3(b). The variation of moisture is investigated by observing the isolines of θ_e from the figure. It is observed that there is no major change in values of θ_e and hence of moisture from one day to the next. Higher values of θ_e at a level, as compared to the level mean, appear to be due to convection, which causes the air to be uplifted bringing moist air from lower regimes to the higher tropospheric levels. It is observed that on the days of decrease of moisture, lower values of θ_e from upper atmosphere subsided down. Hence, it can be concluded that the drying of the atmosphere was more due to subsidence of upper layer dry air than due to horizontal advection.

Similarly, for Delhi, Figs. 4(a&b) represents the vertical profiles of specific humidity departures from level mean and equivalent potential temperature respectively of the atmosphere. It is observed that for the first half of the season, rainfall days are reflected by deep layer moisture increase in the lower troposphere. This confirms the findings of Table 6 with respect to moisture supply from the anticyclone over the Arabian Sea in the initial part of the season. However in the month of May, the signature becomes less distinct and moisture in the mid and upper troposphere increase irrespective of the occurrence of rainfall. The variation of moisture content in the atmosphere at a particular level may be due to either subsidence or advection. The dry lower troposphere as demonstrated by Fig. 4(a) is also reflected in Fig. 4(b) as exceptionally low values of θ_e. These values are substantially lower than any values existing on previous or later day throughout the atmosphere. Also the lowering of θ_e values are of the order of 20° C from one day to the next. This abrupt a change, from one day to the next, could not have occurred through radiative cooling alone. This leads to the conclusion, that the changes in moisture and hence CAPE from day to day is more due to advection of air from surroundings than a result of *in-situ* change in the atmosphere.

5. Concluding remarks

We have analyzed the thermodynamical and dynamical parameters of the atmosphere in relation to the pre-monsoon convective activity over northern India. The two stations selected for analyses - Kolkata and Delhi represent the two regimes of convective activity - namely eastern India and northwest India respectively. From the preceding analyses, the broad conclusions that emerge may be summarized as follows:

While the 1200 UTC value of CAPE at 1000 hPa over Kolkata as well as Delhi shows very poor correlation with the rainfall amount at the beginning of the season, correlation improves slightly towards the end of the season. However, it is encouraging to note that CAPE is better skilled in predicting the occurrence of rainfall on the subsequent day over Kolkata rather than the rainfall amount. On the other hand, 1200 UTC vertical profile of the atmosphere over Delhi does not reveal much of the convective activity over the station, if 24-hours rainfall is taken to be a measure of the convective activity. However, the 6 hours time window selected around the 1200 UTC observation period does reveal a very good threat score and bias score for thunderstorm activity around the station (with or without accompanying rainfall) with 24 hours change (rise) in the CAPE as the predictor for the convective activity of the subsequent day.

One reason for the poor correlation of CAPE with rainfall amount, may be due to the presence of high value of CINE, which acts as barrier to the vertical updraft. So for realization of CAPE as convective activity presence of a supportive dynamic field is found essential.

The nature of the convective activity over Kolkata is found to change and becoming deeper and more dependent on the lower tropospheric positive vorticity field and moisture field as the season advances. Initially the clouds are shallow cumuli, with moisture supply mainly in the middle troposphere, from synoptic systems in association with western disturbances. Enhanced rainfall activity during latter part of pre-monsoon season is due to increased lower tropospheric vorticity field in presence of low level cyclonic circulation over the region and boundary layer moisture incursion from the anticyclonic cell over the Bay of Bengal. For Delhi, the correlation of lower tropospheric moisture with rainfall amount in the initial part of the season reveals a rainfall dependence on moisture influx from the anticyclonic cell over the Arabian Sea. Like Kolkata, the character of the cumuli in association with the convective activity changes with advance of the season. An increasing dependence of the rainfall on the lower tropospheric positive vorticity field does reveal that the convection becomes deeper as the season advances. However, this dependence of rainfall on low level positive vorticity field is less than that over Kolkata indicating that unlike Kolkata dynamic field is not an important initiator of convective activity for Delhi.

It is also evident from this study that day to day variation of moisture levels in the lower atmosphere and hence of CAPE over Kolkata, is due to atmospheric subsidence of dry middle layer air. This is in contrast to Delhi, where horizontal advection is found to be the main reason for daily variation in low level moisture.

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