MAUSAM, **55**, 4 (October, 2004), 549-560

551.510.5

Evolution of the vertical structure of the atmosphere over North-West India during winter season

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(*Received 2 December 2002, Modified 4 December 2003*)

सार – इस शोध–पत्र में दिसम्बर 2001 से फरवरी 2002 तक की अवधि के आँकड़ों का उपयोग करते हुए शीत ऋतु के दौरान दिल्ली पर पश्चिमी विक्षोभों (प.वि.) के परिवर्तन के संबंध में वायुमंडल के संरचनात्मक परिवर्तनों की जांच की गई है। भारत मौसम विज्ञान विभाग के निदर्श विश्लेषण क्षेत्रों के आधार पर दिल्ली में संवहनी उपलब्ध स्थितिज ऊर्जा (सी.ए.पी..ई), संवहनी अवरोधन ऊर्जा (सी.आई.एन.ई.) वर्षणीय जल का अंश और भ्रमिलता जैसे विभिन्न प्रकार के तापगतिकीय और गतिकीय प्राचलों का आकलन किया गया है । यद्धपि स्टेशन पर वर्षा के अधिकांश दिनों में सी. ए. पी. ई. के मान में वृद्धि स्पष्ट रूप से देखी गई है किंतु फिर भी वर्षा होने के लिए यह कोई अनिवार्य परिस्थिति नहीं है और न ही वर्षा की मात्रा सी. ए. पी. ई. से सुसंबद्ध है । दैनिक विशिष्ट आर्द्रता के उर्ध्वाधर प्रोफाइल से पता चलता है कि क्षेत्र के विक्षुब्ध मौसम का प्रत्येक दौर के पहले और उसके साथ में स्टेशन पर गहन सकारात्मक आर्द्रता संबंधी विसंगतियाँ आती हैं । समान विभव तापमान प्रोफाइल से यह ज्ञात होता है कि पश्चिमी विक्षोभ के पथ से संबद्ध आर्द्रता में अचानक वृद्धि क्षेत्र में आर्द्रता के अभिवहन के कारण होती है । इनकी सत्यता सिनॉप्टिक चार्टों से पुनः प्रमाणित की जाती है जो अरब सागर से परिसीमा स्तर में आर्द्रता सभंरण को सिद्ध करती है । वर्षा की मात्रा तापगतिकीय प्राचलों से बहुत अधिक सुसंबद्ध नहीं है किंतु फिर भी वर्षा की मात्रा निम्न क्षोभमंडल के सकारात्मक भ्रमिल क्षेत्र पर काफी निर्भर करती है । यह स्टेशन पर वर्षा की सक्रियता में तीव्र गतिक प्रणोदन को दर्शाती है । निम्न क्षोभमंडल में रिज लाइन के उत्तर की ओर झुकाव के साथ वर्षा से यह पता चलता है कि स्टेशन पर वर्षा की सक्रियता मुख्यतः पश्चिमी विक्षोभ के ऊपरी स्तर की द्रोणियों में संबद्ध प्रेरित सतह निम्न दाब के कारण होती है । अंतः स्टेशन पर वर्षा के सक्रिय प्रेरण में तथा इस कारण इस क्षेत्र में इस मौसम के दौरान मुख्यतः गतिक और वायुमंडल में स्थानीय संवहनी संरचना इस सम्पूर्ण प्रक्रिया में बहुत महत्वपूर्ण भूमिका नहीं निभाती है ।

ABSTRACT. This paper examines the structural changes of the atmosphere in relation to the passage of Western Disturbances (WD) over Delhi, during winter season using data for the period December 2001 to February 2002. Various thermodynamic and dynamic parameters such as Convective Available Potential Energy (CAPE), Convective Inhibition Energy (CINE), precipitable water content and vorticity over Delhi have been computed based on model analysis fields of India Meteorological Department. Although, a clear increase in the value of CAPE is noticed on most of the days of occurrence of rainfall over the station, this is not a necessary condition for the occurrence of rainfall nor is the amount of rainfall very well correlated to the value of CAPE. The vertical profile of the daily specific humidity reveals that each spell of disturbed weather is preceded and accompanied by deep positive moisture anomalies over the station. The equivalent potential temperature profile shows that this sudden increase in moisture associated with the passage of WD is due to advection of moisture over the station. This again is validated by the synoptic charts, which demonstrate the moisture feed in the boundary layer from the Arabian Sea. The rainfall amount is not very well correlated to the thermodynamic parameters considered. However, rainfall amount is found to have a stronger dependence on positive vorticity field of the lower troposphere. This reflects the stronger dynamic forcing of the rainfall activity over the station. The northward tilt of the ridge line in the lower troposphere in association with rainfall demonstrates that the rainfall activity over the station is primarily caused by the induced surface low in association with the upper level troughs of a WD. Hence the trigger for the rainfall activity over the station and hence this region, during this season is primarily dynamic in nature and local convective structure of the atmosphere does not play a very determining role in the entire process.

Key words – CAPE, CINE, Equivalent potential temperature, Western disturbance.

1. Introduction

Western Disturbance (WD) is the main rain producing system over the northern parts of the country (India) during winter months (December, January and February). This system is of extra-tropical origin and is synoptically seen as an upper tropospheric westerly trough moving from west to east. Such troughs are frequently seen in the upper atmosphere over northern India during this season. However, not all of them bring rainfall over India. Occasionally, in association with these trough, induced lower tropospheric cyclonic circulations or cut-off lows are also seen (Rao and Srinivasan, 1969). Rainfall very often occurs in association with the passage of such systems over north-west India.

While some rainfall events are of high intensity, in majority of instances, the rainfall is light to moderate and is widespread. Most studies of tropical rainfall activity concentrate on the analysis of the tropical atmosphere around the days when severe disturbed weather was realized (Weston, 1972, Dhar and Sinha, 1994, Chaudhuri and Chattopadhyay, 2001). Severe weather conditions generally take place only when both thermodynamic and dynamic factors support convection as well as the rainfall process (Miller, 1972). However, the low intensity and widespread rainfall in association with WD, which is characteristic of this season is also important, especially from an agro meteorological point of view. In such systems, not only the synoptic scale settings, but also the mesoscale features prior to and during the event play an important role in deciding the severity of the disturbed weather conditions. Given that major weather events occur when dynamic and thermodynamic factors mesh properly, there are two other possible combinations that can give rise to less severe disturbed weather: weak dynamics and strong thermodynamics (Maddox and Doswell, 1982) or strong dynamics and weak thermodynamics. Thunderstorm severity is generally proportional to draft strength, and the physics of convection suggests that strong drafts (both up and down) are far more likely in cases where the thermodynamic instability is high, regardless of dynamic factors. When the instability is not present at the outset, the dynamic factors must operate to produce it. The aim of this study is hence two fold :

(*i*) To determine the main triggering mechanism that causes rainfall over the representative station.

(*ii*) To study the interaction of the synoptic scale with the meso-scale forcings that produce disturbed weather.

Delhi (Lat. 28.6° N / Long. 77.2° E) is selected as representative of the atmosphere over north-west India. The station received rainfall during the passage of WDs throughout the months of January and February 2002 when the study was conducted. The thrust of this study is on the analysis of the evolution of the atmosphere during the winter season (1 December 2001 to 27 February, 2002) in relation to the passage of synoptic systems that bring rainfall to northern India. This data period captures distinct cases of 12 days of rainfall in association with 5 WDs over Delhi.

2. Source of data

The primary data used are from the daily analysis fields (at resolution of 1° × 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 Delhi, corresponding nearest grid point data are considered. All thermodynamic and dynamic parameters are computed based upon 1200 UTC analysis fields. Rainfall data for the station on any day is the 24 hours total rainfall for a day as reported at 0300 UTC.

3. Methodology

India is in the tropics and the atmosphere over the entire country is mostly barotropic throughout the year. Rainfall in tropical climate is mostly of convective nature. It is with this assumption, that this study is initially focussed on the thermodynamics of the atmosphere over Delhi.

Convective Available Potential Energy (CAPE) has often been studied in relation to convective activity in the tropics (Bhat *et al.*, 1996; Williams and Renno, 1993; (hereafter WR), McBride and Frank, 1999; (hereafter MF), Chaudhury and Chattopadhyay, 2001). Since it is strongly dependent on both surface as well as upper level temperature and humidity, it accounts for both large scale atmospheric changes due to passage of synoptic systems which mainly affect the upper atmosphere, as well as boundary layer atmospheric forcing reflecting the mesoscale changes (MF). CAPE provides a measure of the maximum possible kinetic energy that a parcel can acquire, starting from rest and moving vertically due to gravitational convection. It has been shown to play an important role in mesoscale convective systems (Moncrieff and Miller, 1976), especially in the tropical atmosphere (Bhat *et al.*, 1996). In this study surface values of CAPE have been considered, as it has been observed in general that air parcels in the tropics raised from above 900 hPa rarely become positively buoyant. Following the method described by WR and presuming that the parcel undergoes pseudoadiabatic ascent,

$$\text{CAPE} = -\int_{P_{\text{LFC}}}^{P_{\text{LNB}}} (T_{\text{vp}} - T_{\text{ve}})\text{R}_{\text{d}}\,\text{d}(\ln P) \qquad (1)$$

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 1000 hPa 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.

R_{d} : 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).

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

$$\text{CINE} = -\int_{P_{\text{SFC}}}^{P_{\text{LFC}}} (T_{\text{vp}} - T_{\text{ve}})\text{R}_{\text{d}}\,\text{d}(\ln P) \qquad (2)$$

where P_{SFC} : is the surface pressure level *i.e.*, 1000 hPa. This is calculated, again presuming that the parcel undergoes pseudoadiabatic ascent. Computation steps of CAPE and CINE (Sen Roy and Roy Bhowmik, 2003 (hereafter SRRB)) 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.

(*iv*) 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.

Equivalent potential temperature of an environmental pressure level designated by θ_{e} is the potential temperature a parcel would have acquired if all its moisture where θ is the were condensed out and the resultant latent heat used to warm the parcel. After (Holton, 1992), it is mathematically expressed as

$$\theta_{\text{e}} = \theta.\text{e}^{\frac{\text{L}_{\text{c}}\text{q}_{\text{s}}}{\text{C}_{\text{p}}T}} \qquad (3)$$

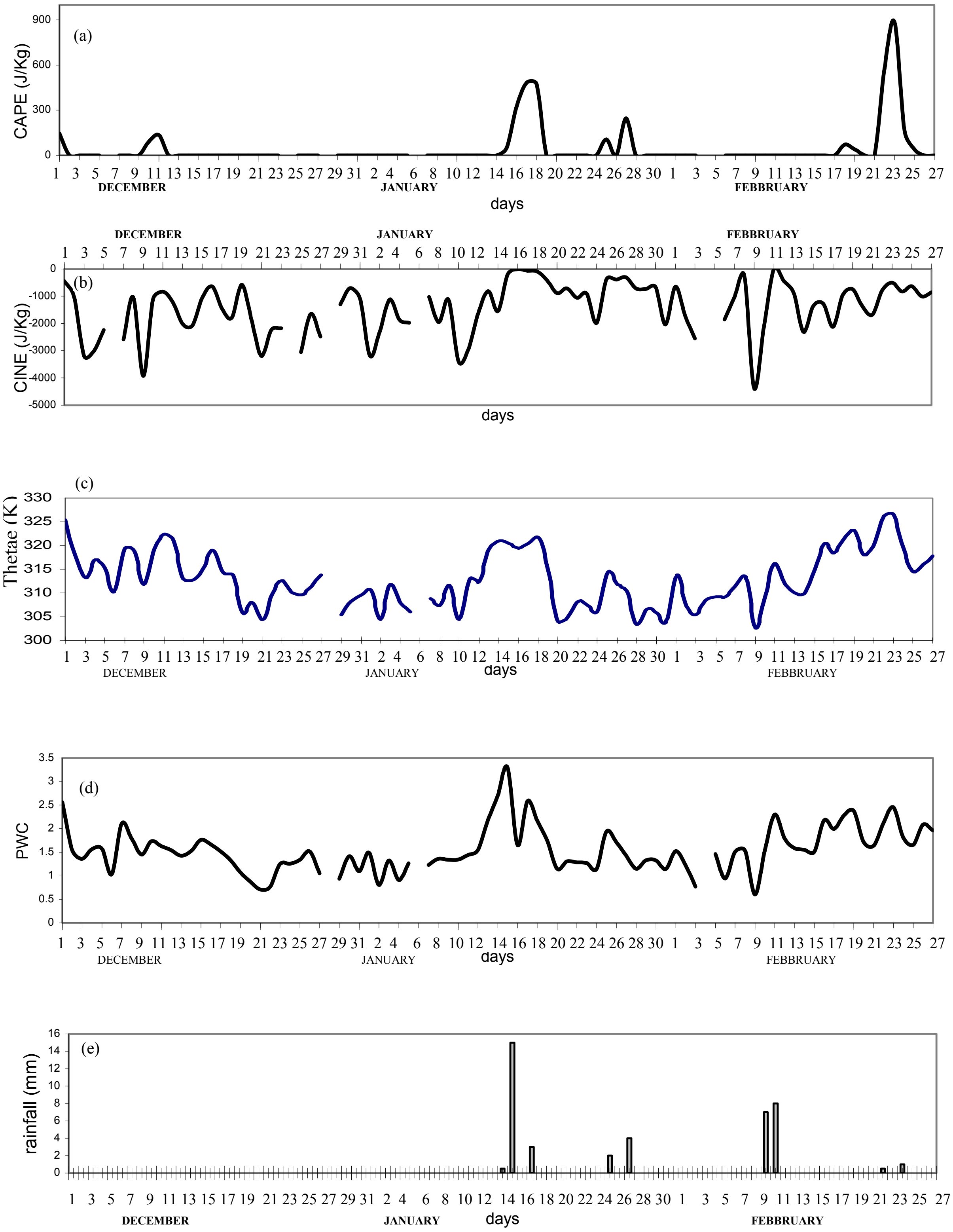
where θ is the potential temperature of a parcel originating at the environmental level

L_{c} is the latent heat of condensation

T is the temperature of the saturated parcel.

q_{s} is the saturation mixing ratio.

C_{p} is the specific heat at constant pressure.



Figs. 1 (a-e). (a) Day to day variation of CAPE (J/kg) values over Delhi for the period from 1 December 2001 to 27 February, 2002, (b) same as (a) except for daily values of CINE (J/kg) over the station, (c) same as (a) except for daily values of surface equivalent potential temperature (°K), (d) same as (a) except for daily values of precipitable water content (g/cm^2) and (e) same as (a) except for 24 hours observed rainfall (mm)

TABLE 1

Correlation coefficient of 24 hour rainfall amount with different thermodynamic parameters at station

	CAPE	CINE	P_{LFC}	PWC	θ_e (surface)
Rainfall amount	0.09	0.46	0.27	0.44	0.14

TABLE 2

Skill scores of CAPE (using threshold value as 52.3 J/kg) with occurrence of rainfall activity

Station name : Delhi	Bias score	Threat score
CAPE Threshold value 52.3 J/kg	1.05	0.88

The definition of virtual potential temperature θ_v used here is given by (Holton, 1992),

$$\theta_v \cong \theta(1 + 0.61 q_v) \tag{4}$$

neglecting liquid water specific humidity, which is relatively negligible in above equation. In the above equation, q_v is the specific humidity of water vapour.

Convective instability only is not sufficient to study the nature of deep convection over a region. Sufficient moisture on the atmospheric column is another requisite for the deep convection to sustain. The Precipitable Water Content (PWC) represents the depth of moisture in the atmospheric column, and is given by :

$$\mathrm{PWC} = \frac{1}{\mathrm{g}} \int_{P_{\mathrm{sur}}}^{P_{\mathrm{top}}} q \, \mathrm{d}P \tag{5}$$

Where the limit of the integration is from the surface to the top of the atmosphere upto, which the value of specific humidity q is non zero and g is the acceleration due to gravity.

The dynamic forcing is analysed from the relative vorticity profile of the atmosphere over the station.

Computation and comparison of some of the commonly used categorical statistics, *i.e.* skill scores like bias and threat score are also included in this study (Stanski *et al.*, 1989). A Bias score (B) and a Threat score (T) are defined as

$$\mathrm{B} = \frac{\mathrm{F} + \mathrm{H}}{\mathrm{M} + \mathrm{H}} \tag{6a}$$

$$\mathrm{T} = \frac{\mathrm{H}}{\mathrm{F} + \mathrm{M} + \mathrm{H}} \tag{6b}$$

where

F : Number of false alarms (occurrence of rainfall expected and not realised)

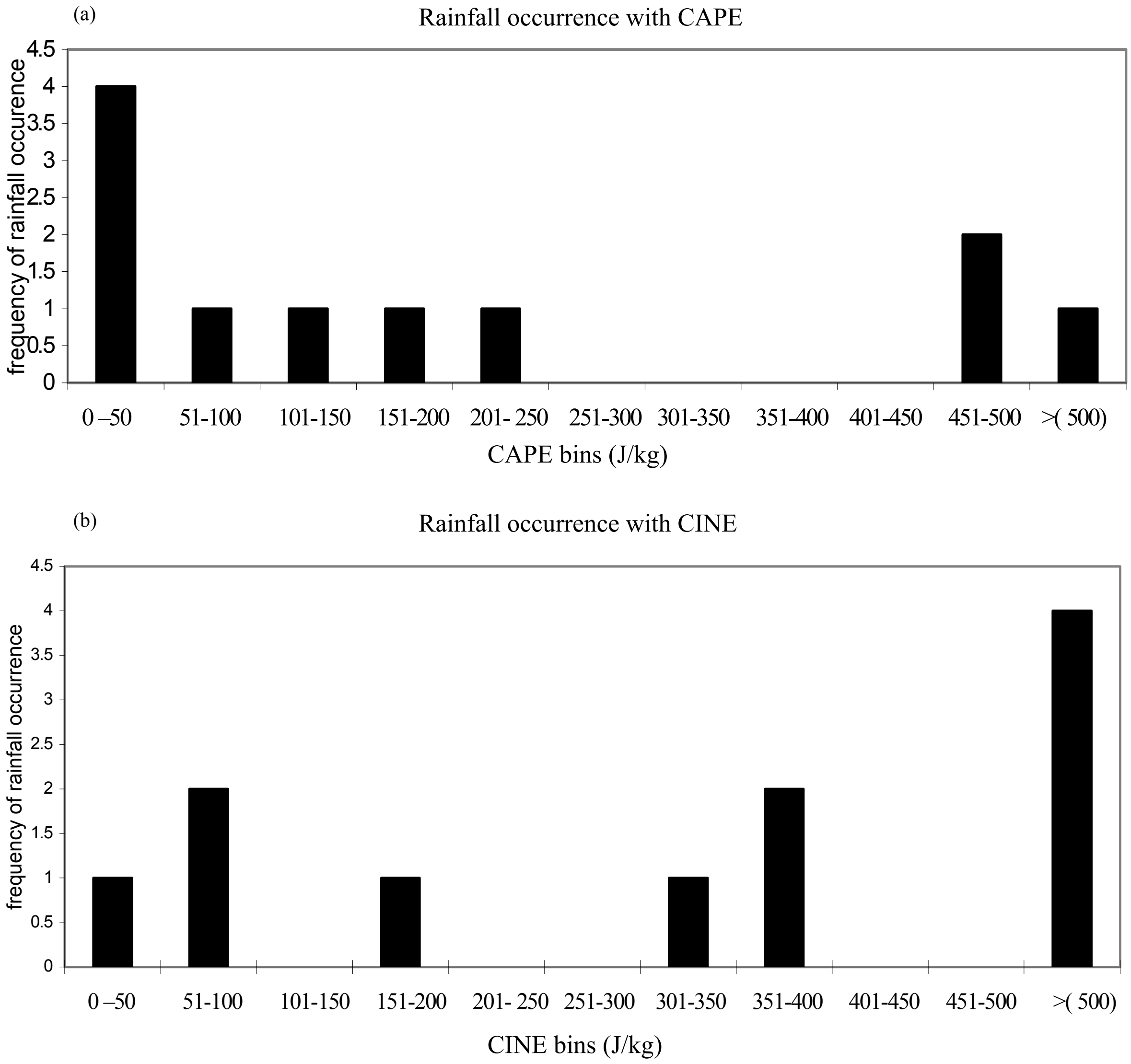
M : Number of misses (non-occurrence of rainfall expected but rainfall occurred)

H : Number of hits (expected occurrence as well as non-occurrence of rainfall is realised).

Bias score and Threat score become unity in case F = M = 0. When a bias score is less than unity it indicates that the event (in this case occurrence of rainfall on a particular day) is underestimated; otherwise it is overestimated. For the best correspondence of the two events, Bias and Threat Scores both become 1.

4. Results and discussion

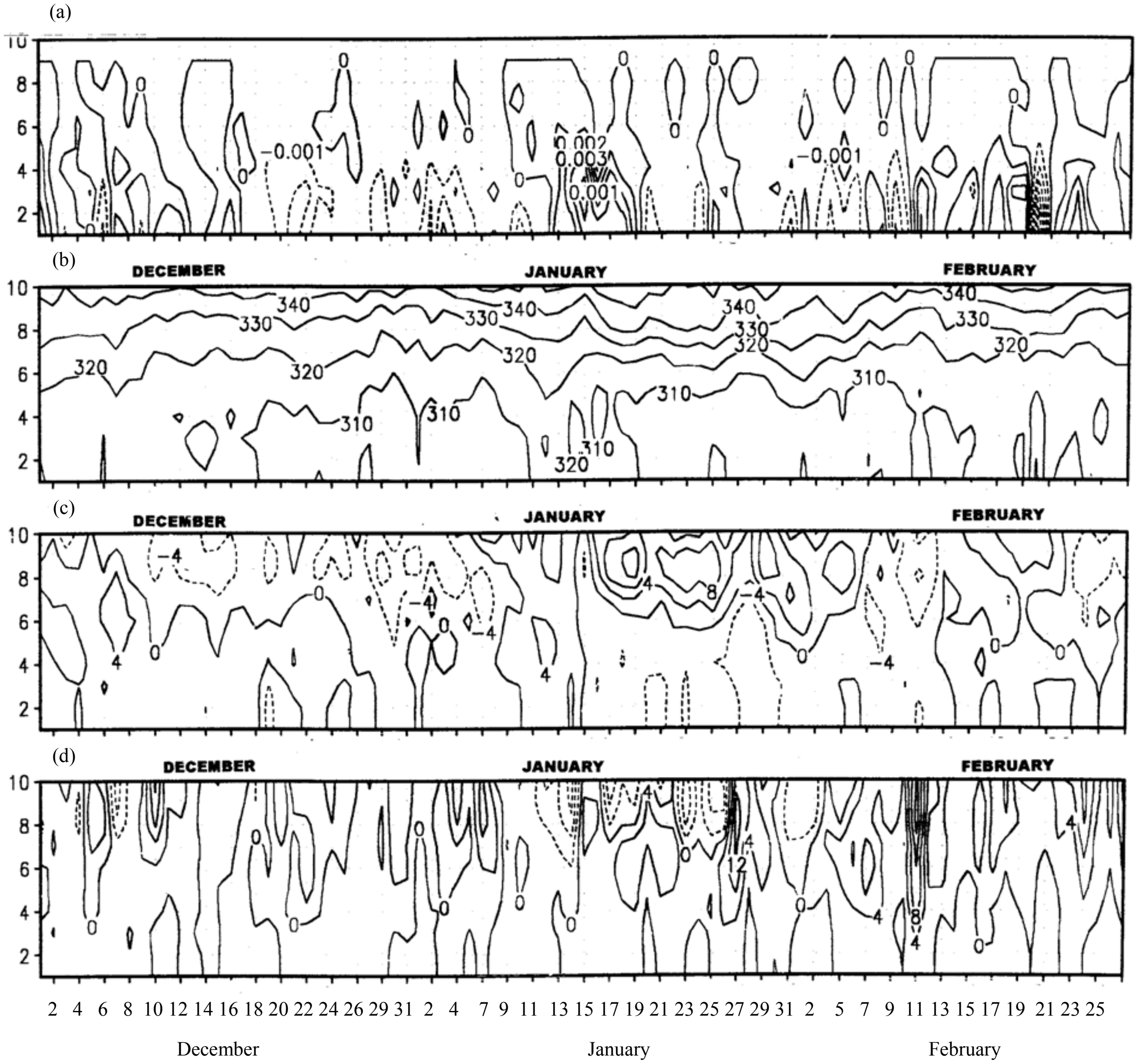
Fig. 1(a) represents the daily variation of CAPE (Eqn. 1) of a surface parcel over Delhi during the winter season, from 1 December 2001 to 27 February 2002, while Fig. 1(b) represents the daily variation of CINE (Eqn. 2) over Delhi during the corresponding period. It may be noted, that the days on which value of CAPE was reported as zero, it implies that the level of free convection was not observed below 200 hPa. Under these circumstances, the value of CINE which are shown to be arbitrarily large, have no significance and may be ignored. Figs. 1(c&d) represents the 1000 hPa profile of equivalent potential temperature (Eqn. 3) and precipitable water content (Eqn. 5) respectively over Delhi. A few days on which 1200 UTC data could not be downloaded due to computer problem are excluded. Fig. 1(e) represents the daily rainfall over Delhi for the period under consideration, as measured at the 0300 UTC observation of the subsequent day.



Figs. 2(a&b). (a) Frequency of rainfall occurrence per interval of CAPE values over the station and (b) same as (a) except for intervals of CINE values over the station

4.1. *CAPE in relation to convective activity*

As is clear from Table 1, poor correlation exists between rainfall amount and the value of CAPE over the station for the period as a whole. Moreover, since value of CAPE is zero on most days, it indicates the stable nature of the atmosphere during most of the season. Weak negative correlation between rainfall amount and CAPE was previously reported by MF during Australian monsoon season around the Gulf of Carpentria in the tropics, and also by Thompson *et al*. (1979). Weak positive correlation of CAPE with rainfall over Delhi for the pre-monsoon season was reported by SRRB. However, as is clear from Figs. 1(a&d), correspondence between incidence of positive values of CAPE over the station and the occurrence of rainfall activity is quite good, especially for the (WD) systems in the month of January, when there is a nearly one-to-one correspondence between the two. This correspondence between the two parameters decreases somewhat, for the systems in the months of December 2001 and February 2002, when it is observed that a good thermodynamic field has not necessarily translated itself into rainfall over Delhi or adjoining areas and *vice versa*. To quantify this correspondence between the thermodynamic parameters and rainfall occurrence as an event, bias and threat skill scores Eqn. 6(a & b) are calculated for CAPE with respect to occurrence of rainfall on the same day over the station for the season as



Figs. 3 (a-d). (a) Vertical profile of specific humidity (gm/gm) field departures from the level mean over Delhi, for the period 1 December 2001 to 27 February 2002. Vertical levels : 1 - 10 indicate pressure levels (hPa) 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200 respectively. Contour interval (0.001gm/gm) in solid denotes positive departures from the level mean while dashed lines indicate negative departures from the level mean, (b) same as (a) except for equivalent potential temperature (°K) field, (c) same as (a) except for departures of virtual potential temperature field from the level mean values at contour interval of 4 °K and (d) same as (a) except for vorticity field

a whole and are shown in Table 2. Using a threshold value for CAPE as 52.3J/kg (the minimum non-zero value of CAPE associated with occurrence of rainfall on the same day), it is observed that CAPE has very good skill scores (bias = 1.05 and threat = 0.88) to predict the occurrence/ non-occurrence of thunderstorm activity over Delhi. Similar results have also been obtained in the studies of Bhat *et al*. (1996) and SRRB.

Rainfall dependence on CINE is, however, surprisingly strong (CC = 0.46). Since CINE inhibits the convection over an area, in some instances decrease in the absolute value of CINE may occur under the effect of an appropriate trigger, which decreases the capping inhibitory energy and convection may then take place. The nature of this trigger is investigated in the subsequent sections.

TABLE 3

Correlation coefficient of CAPE with different thermodynamic parameters at Station

	CINE	P_{LFC}	θ_e (surface)
CAPE at station	0.35	0.76	0.49

TABLE 4

Correlation coefficient of relative vorticity with different thermodynamic parameters

Vorticity at →	1000hPa	850 hPa	700 hPa	500 hPa	200 hPa
Rainfall amount	0.48	0.45	0.29	0.29	0.17
CAPE	0.28	0.27	0.16	0.10	0.13
CINE	0.37	0.39	0.40	0.34	0.09
P_{LFC}	0.27	0.23	0.14	0.18	0.17

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 CINE is low. For tropical regions, it has been observed that CINE of the order of 20 J/kg is strong enough to act as a barrier to vertical updrafts from surface reaching the P_{LFC} and beyond (WR). On comparing Figs. 1(a&b), it can be seen that during the period under consideration, on almost all days with non-zero values of CAPE, value of CINE is considerably higher than 20 J/kg. When one tries to correlate the rainfall frequency with the value of CAPE and CINE graphically, as in Figs. 2(a&b), a very anomalous trend emerges. It is observed that rainfall occurrence is apparently favoured by low positive values of CAPE. This seems to imply that convective mechanism plays a less dominant role in initiation of precipitation than in other seasons. This requires further investigation by examining the vertical profile of the atmosphere with respect to other dynamic and thermodynamic parameters.

4.2. *Vertical structure of atmosphere in relation to rainfall activity*

Fig. 1(d) and Table 1 demonstrate that the correlation between the precipitable water content of the atmosphere and rainfall, is quite good (0.44). The precipitable water content is the moisture content of the atmospheric column above the station and the positive correlation of humidity with the rainfall is somewhat expected but variation of humidity through the cross-section of the atmosphere will be studied in greater detail in this section. The essential features of the vertical profile of the atmosphere as well as the nature of changes in the profile in association with rainfall over Delhi will be brought out with the help of Figs. 3(a-d).

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. Increase or decrease in the value of CAPE on a daily basis may be primarily dependent on the moisture content of the corresponding level of parcel origin. Hence, analysis of the vertical profile of moisture content of the atmosphere is essential to understand not only the reason for the daily variation of CAPE but also of rainfall. To examine the behaviour of the vertical profile of moisture in the atmosphere with respect to convection, the deviations of specific humidity from the level mean for this data period have been plotted in Fig. 3(a). It is observed that the atmosphere in general is less moist in January except for the periods with disturbed weather, as compared to December and February. This is also borne out by the precipitable water content profile in Fig. 1(d). The periods of rainfall occurrence are reflected by deep layer positive anomalies in the specific humidity field. These anomalies may either be the cause for increased convection over the region or may be a result of the overturning air as a result of increased convection over the area. On careful analysis it is seen that these positive anomalies appear to originate in the mid/upper troposphere and gradually extend downward to the lower troposphere on the days of actual incidence of rainfall. However, as in the CAPE field, not all occasions of high positive anomalies are noticed in the form of rainfall, especially in December.

The variation of moisture content in the atmosphere at a particular level may be due to either subsidence or advection. To investigate the reason, the vertical profile of the corresponding conserved quantity - equivalent potential temperature (Eqn. 3) is investigated in Fig. 3(b).

The moist lower troposphere around a rainfall event, as demonstrated in Fig. 3(a) is also reflected in Fig. 3(b) as exceptionally high values of θ_e. These values are substantially higher (of the order of 8 – 10° K) than any values existing on previous or the latter day throughout the atmosphere. This nature of abrupt change, from one

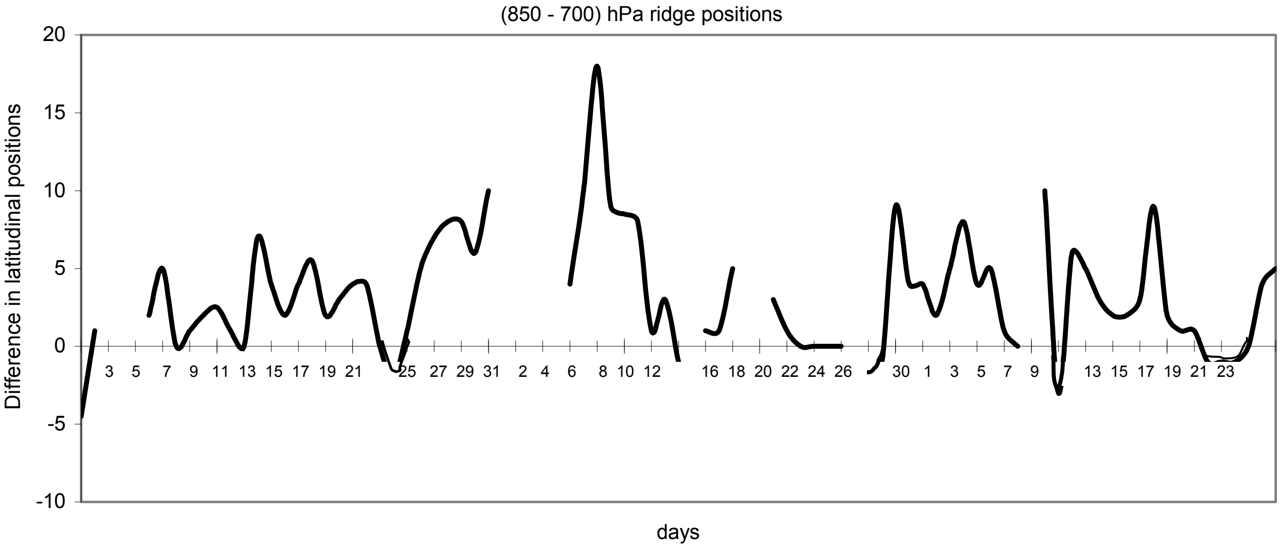


Fig. 4. Difference in the daily latitudinal variation of the 850 hPa and 700 hPa ridge positions over longitude 77.3 ^{0}N (Delhi) averaged over 5 degree longitude.

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. Similar results were also obtained for pre-monsoon season over Delhi (SRRB). This is also borne out by the synoptic charts (not shown), which reveal that the disturbed weather over Delhi is primarily in association with the moisture feed from the Arabian Sea.

Previous studies (SRRB) have also shown a very strong dependence of the parameter $\mathrm{CAPE}_{\mathrm{surface}}$ on the surface moisture as well as on the surface equivalent potential temperature for North India during pre-monsoon season. Table 3 lists the correlation of 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 (0.49). As it is evident, a moderate correlation does exist between CAPE and equivalent potential temperature. This could 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. However the correlation is not so strong as it is in the pre-monsoon season. This may be because of the fact that the day to day modifications in the value of CAPE during this season may be due to positive area variations in the upper atmosphere (MF). The value of CAPE is seen to be primarily dependent upon the level of free convection (CC = 0.76).

Following the methodology of Betts (1974), Cohen and Frank (1989), the gravitational stability of the atmosphere is best represented through examining the vertical stratification of the density field as shown by vertical profile of the anomalies of the virtual potential temperature (θ_v) (Eqn. 4) in Fig. 3(c). When the WD is over the station, it is observed that lower atmosphere is cooler than normal while the upper atmosphere has positive anomalies. It can be inferred that the density changes more sharply with height and the atmospheric lapse rate increases. This situation is very favourable for the parcel instability in the presence of a trigger, which in this case is provided by the synoptic systems over the station.

The thermodynamic parameters considered in this paper are a measure of the convective potential of the atmosphere. The lack of strong correlation between thermodynamic parameters and rainfall over Delhi during the period under consideration may imply that the majority of rainfall events realized during this season is not necessarily of convective origin. So the dynamic field is essential for actual realization of rainfall activity at station. To investigate this possibility, the correlation between vorticity of the atmosphere at different levels and rainfall is computed in Table 4. It is observed that, lower tropospheric positive vorticity is well correlated with rainfall amount. This is unlike observations for the Indian region in the pre-monsoon season when the correlation is poorer (SRRB). Many authors, (Banerjee *et al*., 1978), have reported that advection of anti-cyclonic vorticity in the upper layers in association with western disturbances

TABLE 5

Skill scores of 850 hPa -700 hPa latitudinal position (using threshold value as 0°) with occurrence of rainfall activity

Station name : Delhi	Bias score	Threat score
	1.14	0.80

enhanced the instability associated with the disturbance over the station. Fig. 3(d) represents the anomaly profile of the relative vorticity field. We observe that, high anticyclonic vorticity in the upper troposphere are found only associated with the systems in the month of January (14-17 and 25-27 January). On the other hand, for the systems in the month of February, a high positive vorticity at all levels appears to favour the rainfall activity as noticed in this data period.

The stronger dynamic support and poorer thermodynamic support to most instances of occurrence of rainfall, leads to the presumption that this rainfall is non - convective in nature and is not associated with thunderstorm activity. In this regard, the daily 24 hour weather logbook for Delhi (Palam) as well as Delhi (Safdarjung) was examined for report of any thunderstorm activity by observer in association with the rainfall activity over station. As can be noted from Fig. 1(e), on most occasions when rainfall was realised in spite of poor thermodynamic forcing (CAPE = nearly zero), no lightning or thunder was reported by observer in association with the rainfall. Hence it may be concluded, that during this season, CAPE and the associated thermodynamic parameters are better predictors of thunderstorm activity over this region, rather than the actual rainfall amount.

4.3. *Ridge position in relation to rainfall activity*

While the previous section brings out the support of the lower tropospheric dynamic field to the rainfall, in this section this dependence is investigated further from synoptic consideration. Fig. 4 represents the daily latitudinal variation of the ridge positions over longitude 77.3° N (Delhi) averaged over 5 degree longitude about the Delhi longitude. The difference in the latitudinal positions of 850 hPa and 700 hPa is plotted in Fig. 4. A very definite trend emerges from the above figure. On most days, a positive difference is noticed, which indicates, implying a relatively southward location of the ridge line at 700 hPa as compared to its position at 850 hPa. This general southward tilt in the ridge line in the vertical is characteristic of this season and has been observed by other authors (Banerjee *et al*., 1978). However, most cases of rainfall activity recorded during this season are reflected by a zero or negative value in the difference in latitudinal positions implying a reversal in the tilt of the ridge line in association with disturbed weather to the north of the ridge line at 850 hPa. The correspondence increases as the season progresses and is especially true for the systems in February (10-11 and 21-25 February). The above result is quantified in Table 5, where the skill scores are computed about a threshold difference of zero degrees between the latitudinal positions of the ridge line at 700 hPa and 850 hPa. The values of the skill scores (bias score = 1.14 and threat score = 0.80) are close to 1 and reflect the close correspondence of the two events. This northward tilt in the ridge position in association with rainfall occurrence is observed only in the lower troposphere. One reason for this nature of variation of the ridge position could be, that the actual rain producing systems in association with the western disturbance are shallow lows induced by the upper level westerly troughs. These shallow induced lows push the dynamic ridge line of the lower troposphere very much south of its normal position until the slope of the ridge line takes on a vertical or northward tilt. This implies that the rainfall activity over the station occurs mainly in association with the induced lows at the surface in association with WDs, and occasions of rainfall occurrence over the station due to localised convection are very few.

The structure of the atmosphere observed during this season when compared to the pre-monsoon season as observed over Delhi (SRRB), brings out some interesting results. The lack of mesoscale thermodynamic support to the rainfall is common to both the seasons, especially for the first half of the pre-monsoon season. However, unlike pre-monsoon season, the dynamic field associated with synoptic scale systems like WDs plays a very decisive role in pulling moisture from over the Arabian Sea thereby causing rainfall. During the pre-monsoon season, the ridge position shifts further northward, and the WDs pass very much north of the Indian latitudes, and thus have less effect on the weather over northern India.

5. Concluding remarks

The thermodynamic changes of the atmosphere during winter months (December 2001-February 2002) over Delhi in relation to the passage of WD have been investigated in this paper. Study shows that correlation between the value of CAPE and the rainfall amount over the station is poor. However, a clear correspondence between the positive value of CAPE and the occurrence of rainfall over the station is reflected in the results of skill and bias scores. An important feature that is brought out in this study is that the sudden increase of moisture before the commencement of rainfall activity is due to external advection of moisture during the passage of WD, as revealed by vertical time section of θ_e. The result is further validated with the synoptic charts and the tilt in the ridge position with height, which demonstrated boundary layer moisture feeding from the Arabian Sea. In contrast to the poor correlation coefficient between rainfall amount and thermodynamic parameters, rainfall amount is very well correlated with the positive vorticity of the lower troposphere. This reflects the greater influence of dynamic forcing compared to the thermo dynamical support in causing rainfall activity over the station. This is unlike the weak dynamic forcing (stronger thermo dynamical support) during premonsoon season (SRRB).

The study with one season data shows sufficiently promising results to warrant further investigation of the atmosphere over North-West India, with larger data sets of winter season in relation to the passage of WDs that bring rainfall to the region.

Acknowledgements

Authors are grateful to the Director General, India Meteorological Department, New Delhi for providing all facilities to carry out this work. Authors are thankful to Dr. P. K. Kundu of Vidyasagar University for his valuable comments. Authors are also thankful to Shri S. R. Kalsi, Additional Director General of Meteorology, Shri R. C. Bhatia, Additional Director General of Meteorology, and Dr. Sant Prasad, Deputy Director General of Meteorology (Satellite Meteorology), India Meteorological Department, New Delhi for their keen interest and encouragement in this study. The computation work for this study was carried out using the mainframe computer system CYBER 2000U of India Meteorological Department, New Delhi.

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