Analysis of thermodynamics of the atmosphere over northwest India during the passage of a western disturbance as revealed by model analysis field

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This paper analyses the vertical structure of the atmosphere over Delhi as representative of atmospheric conditions over northwest India during the passage of a western disturbance (WD) during January 2002. In association with this WD, Delhi received the first and most abundant rainfall of the winter season on 15 January. This paper explores the thermodynamics of the atmosphere computing CAPE, CINE, moist static energy and other moisture parameters of Delhi based on model analysis fields of India Meteorological Department. The vertical vorticity profiles for this station have also been calculated. A clear increase in the value of CAPE and decrease in the value of CINE is noticed on the days of occurrence of rainfall over the station (15–18 January). The surface moist static energy curve on the other hand, shows a significant increase in value two days prior to the occurrence of rainfall over the station. The precipitable water content profile of the column of the atmosphere above the station is seen to closely follow the rainfall pattern associated with the system. The model analysis field for moisture anomalies reveals fingers of increased moisture in the upper troposphere very much in advance of the actual outbreak of rainfall activity over the station, in association with a WD. Around the time of onset of rainfall activity at the station, these positive moisture anomalies come down to the lower troposphere. It is also observed that just prior to the onset of a WD over the station, due to the moisture influx over the station, the atmospheric density decreases.

WESTERN disturbance (WD) is the main rain producing system over the northern parts of the country (India). Synoptically it is seen as a mid/upper tropospheric westerly trough moving from west to east, occasionally associated with this trough, an induced lower tropospheric cyclonic circulation or cut-off low is also seen[1]. Few of them have sufficient southern reach, to bring adequate rainfall over the entire northern India. Rainfall associated with this system is characterized by mixture of stratiform and convective type of clouds.

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Delhi received the first rainfall (15 mm) of the winter season on 15 January 2002 in association with a WD. The thermodynamics of the atmosphere over Delhi in relation to the passage of this WD have been investigated in this paper using model analysis field.

Methodology and data

According to the parcel theory, CAPE is a measure of the energy realized when conditional instability is released. It has been shown to play an important role in mesoscale convective systems[2], especially in the tropical atmosphere[3]. CAPE provides a measure of the maximum possible kinetic energy, that a convective parcel can acquire, assuming that parcel ascends without mixing with the environment and instantaneously adjusts to the environmental pressure. Only surface values of CAPE have been used in analyses, as it has been observed in the Gulf of Carpentria during the AMEX experiment[4], that air parcels raised from above 900 hPa in the deep tropics rarely become positively buoyant. Following the method described by Williams and Renno[5],

$$\mathrm{CAPE} = -\int_{P_{\mathrm{LFC}}}^{P_{\mathrm{LNB}}} (Tvp - Tve).Rd.\mathrm{d}(\ln P),$$

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, Tve is the virtual temperature of the environment at pressure level P through which parcel rises, Tvp, is the virtual temperature of the parcel at pressure level P through which parcel rises, Rd is the gas (dry) constant.

In cases when P_{LNB} was not found, the above integral was extended from P_{LFC} to 200 hPa[6].

As a possible barrier to the initiation of conditional instability in the presence of high CAPE values, Williams and Renno[5] considered a parameter – the Convective Inhibition Energy (CINE). CINE, from the same data set, is evaluated as follows,

$$\text{CINE} = -\int_{P_{SFC}}^{P_{LFC}} (Tvp - Tve).Rd.\mathrm{d}(\ln P),$$

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

This parameter can act as a possible barrier to the release of convection even in the presence of a high value of CAPE[5].

Initially, attempt was made to calculate CAPE and CINE from Delhi RS/RW dataset. However, it was found later, that on many occasions, CAPE and CINE could not be calculated due to non-availability of 200 hPa (P_{LNB}) data on a daily basis. Hence the primary data used here 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, 3D 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 NCMRWF, New Delhi. To derive the parameters for the station, Delhi, corresponding nearest grid point data are considered.

Results and discussion

Figure 1 *a* represents the daily variation of CAPE and CINE over Delhi from 1 to 31 January 2002 while Figure 1 *d* represents the daily rainfall over Delhi for the period under consideration as measured in the 0300 UTC observation of the subsequent day.

It is observed that on the days of occurrence of rainfall over Delhi, CAPE has non-zero values. CINE value also decreased and is closer to zero as compared to the days with rainfall.

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 less.

Previous studies[4] have shown a very strong dependence of the parameter $\text{CAPE}_{\text{surface}}$ on the surface moisture as well as on the surface equivalent potential temperature. The equivalent potential temperature as defined for use in this study is

$$\theta_e = \theta(Lq_v/c_pT).$$

In the above equation, θ_e is the equivalent potential temperature of the level of origin of the parcel, L is the latent heat of vaporization, q_v is the specific humidity of water vapour, c_p is the specific heat of the parcel at the level of origin while T is the temperature at which the parcel attains saturation, i.e. the LCL of the level of parcel origin.

Figure 1 *c* represents the surface profile of the equivalent potential temperature. As is evident, the days of rainfalls that coincide with the days of non-zero values of CAPE are associated with a sudden increase in the value of the 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.

The precipitable water content profile of the column of the atmosphere above the station as illustrated in Figure 1 *b* is seen to closely follow the rainfall pattern associated with the system.

In an effort to better understand the atmospheric condition over the station during the passage of a WD, the vertical thermodynamic profile of the atmosphere over the station has been studied. Figure 2 represents the vertical time section of the atmosphere over Delhi for the period 1 January to 31 January 2002.

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. 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 Figure 2 *a*. It is observed from the figure that, very much prior to the occurrence of rainfall over the station, positive moisture anomalies appear in the upper troposphere. Around the time of rainfall over the station, these positive moisture anomalies penetrate downward and thereby extend throughout the atmosphere. These anomalies increase on the days of actual rainfall realization, i.e. 14, 15 and 17 January but decrease somewhat on 16 January when there was no rainfall over Delhi. Although positive moisture anomalies are also present in the atmosphere on other occasions, however, the atmosphere is not convective enough for rainfall realization as revealed by the surface profile of CAPE.

The strong signature left by the occurrence of rainfall activity over the station on the surface θ_e field has already been illustrated in Figure 1 *c*. The increase (decrease) in moisture content of the atmosphere can be either due to advection of moist (dry) air from the surroundings or due to *in situ* convection (subsidence). To understand the reason behind the present winter rainfall over Delhi, the vertical profile of the corresponding conserved quantity, equivalent potential temperature θ_e is investigated in Figure 2 *b* while its anomaly with respect to the level mean is plotted in Figure 2 *c*. In association with the system, it is observed that on 14 January, the value of θ_e in the lower troposphere, suddenly increased by about 5 K. It is also observed that on 16 January, when the moisture profile shows decreasing moisture levels in mid troposphere, the equivalent potential temperature also dropped by 10 K in the middle troposphere. This nature of abrupt change, from one day to the next, could not have occurred through radiative cooling alone. This leads us to presume that, the drying (moistening) of the

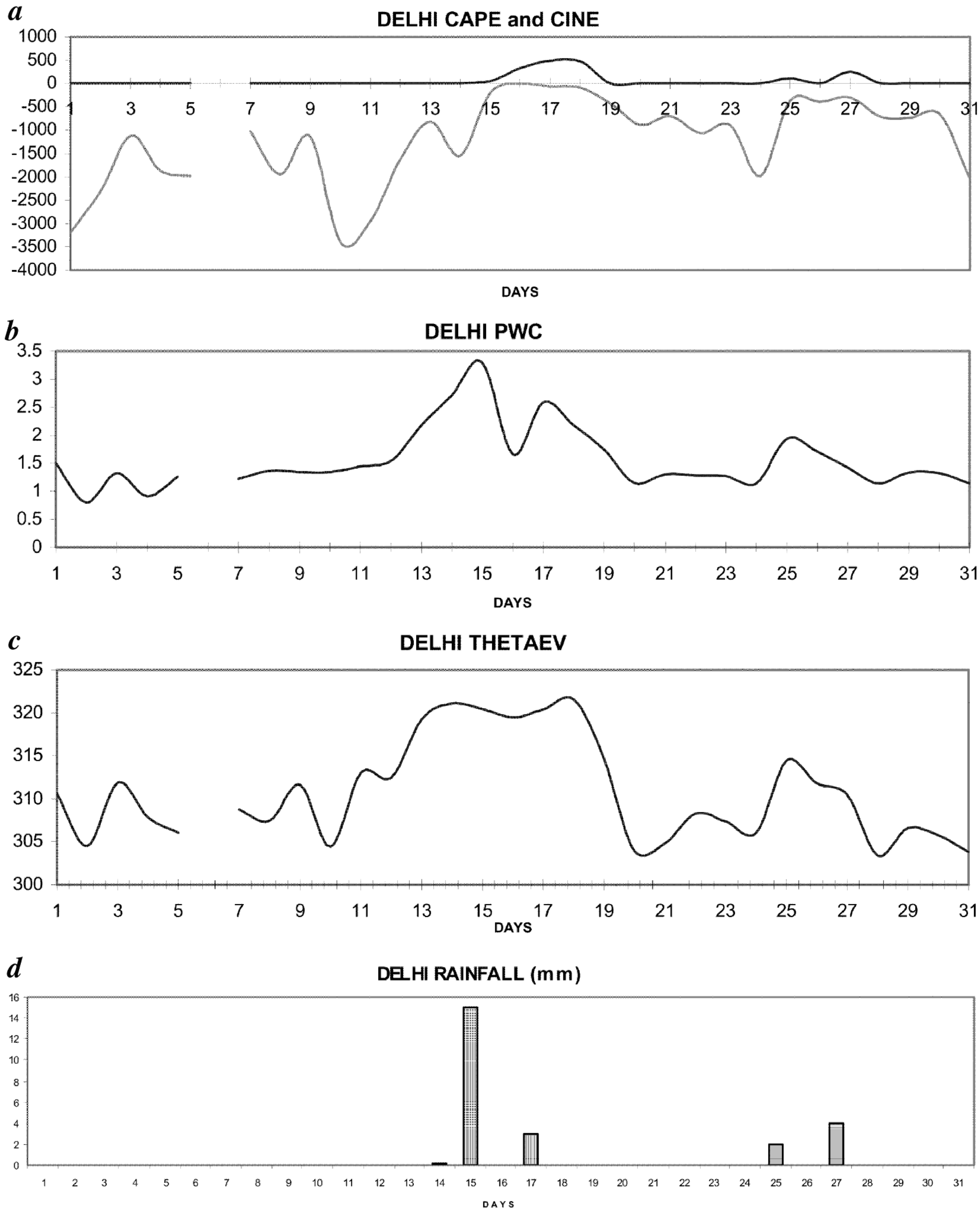

Figure 1. ***a***, Day-to-day variation of CAPE (J/kg) and CINE (J/kg) values over Delhi for the period from 1 January to 31 January, 2002; ***b***, Same as ***a***, except for daily values of precipitable water content over the station; ***c***, Same as ***a***, except for daily values of surface equivalent potential temperature; ***d***, same as ***a***, except for 24-hours observed rainfall (mm).

atmosphere over Delhi in association with a WD is due rather to horizontal advection of dry (moist) air over the station rather than due to *in situ* subsidence (convection) of the atmosphere over Delhi.

Following the methodology of Betts[7] and Cohen and Frank[8], 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 virtual potential temperature (θ_v) in Figure 2 *d* while that of anomalies from the level mean for the experimental period have been plotted in Figure 2 *e*. The definition of virtual potential temperature θ_v used here is given by,

$$\theta_v = \theta(1 + 0.61q_v),$$

neglecting the liquid water specific humidity which is relatively negligible. In the above equation, θ_v is the potential temperature and q_v is the specific humidity of water vapour.

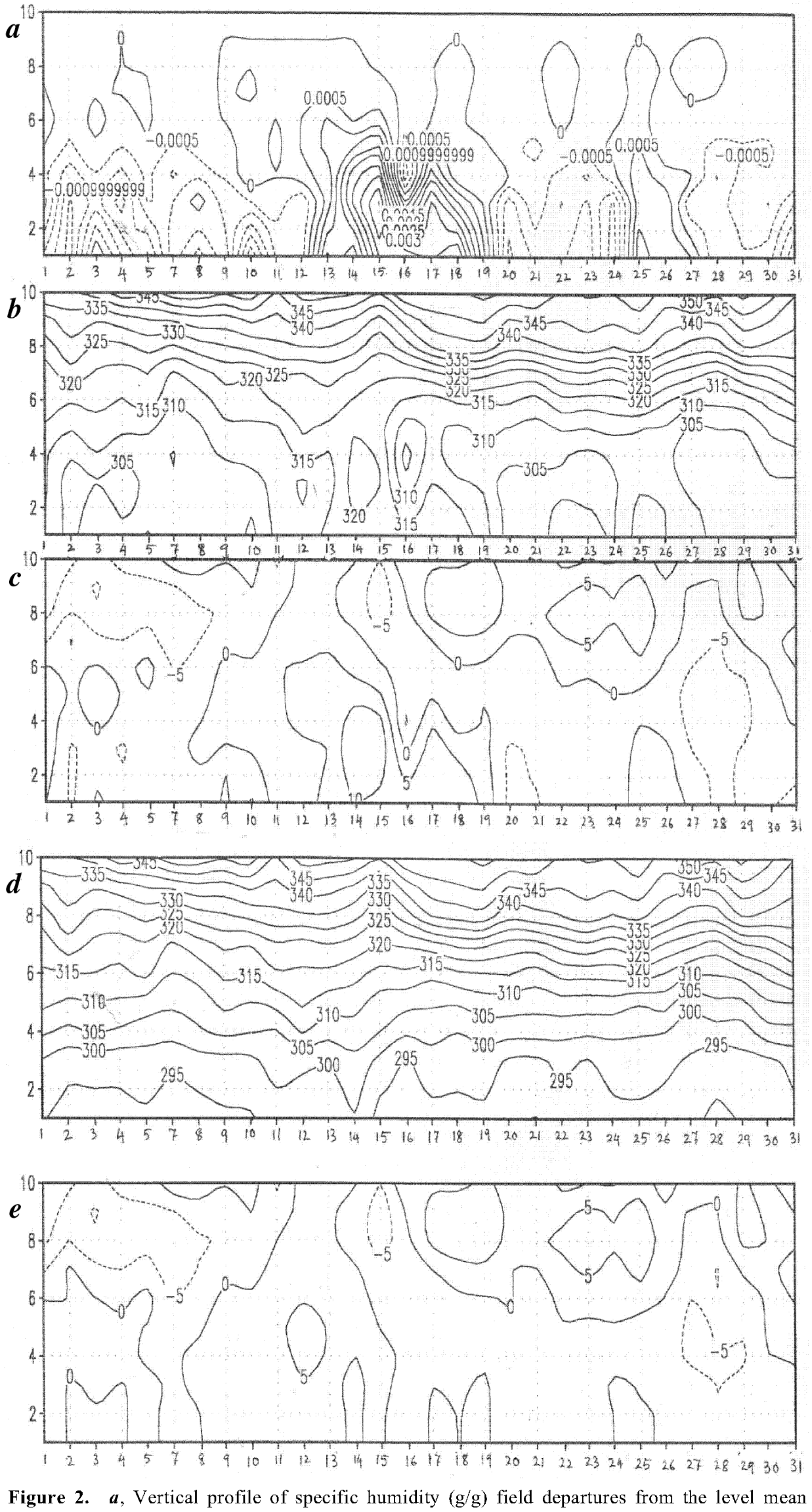

Figure 2. ***a***, Vertical profile of specific humidity (g/g) field departures from the level mean over Delhi, for the period 1 January to 31 January 2001. Vertical levels 1–10 indicate pressure levels (hPa) 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, respectively; ***b***, same as ***a***, except for equivalent potential temperature (K) field; ***c***, same as ***a***, except for departures of equivalent potential temperature (K) field from the level mean values; ***d***, same as ***a***, except for virtual potential temperature (K) field; ***e***, same as ***a***, except for departures of virtual potential temperature (K) field from the level mean values.

It is observed that, the period of rainfall activity is immediately preceded by deep layer warm anomalies of θ_v extending throughout the atmosphere.

Concluding remarks

The thermodynamic changes of the atmosphere over Delhi, in association with the passage of a WD have been investigated in this paper. The parameters studied including CAPE, CINE, equivalent potential temperature, specific humidity and virtual potential temperature have all been calculated using the model analysis fields of India Meteorological Department. A clear increase in the value of CAPE and CINE is noticed on the days of occurrence of rainfall over the station. The surface equivalent potential temperature curve as well as the precipitable water content curve has much higher than average values on the days of rainfall activity over the station. The vertical profile of the daily specific humidity reveals that, very much prior to the actual occurrence of rainfall over the station, fingers of positive moisture anomalies are seen in the upper atmosphere over the station, which gradually come to the surface on the days of actual occurrence of rainfall over the station. This is very much in concurrence with the observed pattern of clouding over a station in association with the passage of a western disturbance. The equivalent potential temperature profile shows that this sudden increase in moisture associated with the passage of a WD, is due to external advection of moisture over the station. This again is validated by the synoptic charts, which demonstrate the moisture feed from the Arabian sea to the cyclonic circulation at the surface generally seen in association with a WD. The local atmosphere during this time of the year is too dry to cause precipitation due to localized convection alone. The virtual potential temperature profile, which represents the gravitational stability of the atmosphere, shows a sudden warming throughout the atmosphere, preceding the actual occurrence of rainfall activity.

This case study shows sufficiently promising results to warrant a further, more general study of the role of CAPE and associated thermodynamic parameters in relation to the winter season rainfall over northern India. A thorough diagnostic study of the nature of atmospheric changes in relation to a WD will go a long way in any model development for the prediction of winter season rainfall over Northern India.

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ACKNOWLEDGEMENTS. We thank Sri S. R. Kalsi, Deputy Director General of Meteorology (Cyclone Warning), and Sri Rajesh Rao, Deputy Director General of Meteorology (Upper Instruments), for their keen interest and encouragement in this study. We are grateful to the Director General, India Meteorological Department for providing all facilities to carry out this work. The computation work for this study was carried out using the mainframe computer system CYBER 2000U of India Meteorological Department, New Delhi.