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Thermodynamic Characteristics Associated with Heavy Rainfall over Uttar Pradesh and Bihar

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ABSTRACT

Uttar Pradesh (UP) and Bihar mainly experience flood due to heavy rainfall during July and August. The probability of detection heavy rainfall over this region by the India Meteorological Department (IMD) is about 50-60%. This is mainly due to the fact that heavy rainfall over these regions occurs due to meso-scale forcings of convection in a large scale synoptic environment. In this study an attempt has been made to find out potential thermodynamic predictors for occurrence of 24hours heavy rainfall over these meteorological sub-divisions during July and August. The upper air radiosonde and radiowind (RS/RW) data during 2001-2005 for month of July and August have been used for this purpose. While heavy rainfall over Bihar and west UP is uniquely related with higher than normal thermodynamic indices of K-index (KI), total totals index (TTI), vertical totals index (VTI) and cross totals index (CTI) over Patna and Gwalior respectively, the heavy rainfall over east UP is related with higher than normal TTI and CTI over Gorakhpur and KI, VTI and CTI over Patna. Above normal (by about 10-15%) relative humidity at different levels up to troposphere over Patna, Gorakhpur and Gwalior stations favours occurrence of heavy rainfall over Bihar, east UP and west UP respectively.

The mean CAPE associated with heavy rainfall over Bihar is greater than 1900J/Kg over Patna. Heavy rainfall over east UP is associated with mean CAPE of greater than 1900J/Kg over Gorakhpur and heavy rainfall over west UP is associated with mean CAPE of greater than 2800 J/Kg over Gwalior respectively. CINE less than 30J/Kg, 40 J/Kg, 60 J/Kg over Patna, Gorakhpur and Gwalior are associated with heavy rain fall over Bihar, east UP and west UP respectively. While Patna and Gwalior have uniquely higher values of CAPE and kinetic factor for heavy rainfall over Bihar and west UP respectively, Gorakhpur does not exhibit so for heavy rainfall over east UP.

Keywords: *Heavy rainfall, Radiosonde, Thermodynamic indices, K-index, Total Total Index and Vertical Totals Index.*

1. Introduction

Bihar and most part of the Uttar Pradesh (UP) lie to the north of the normal position of the monsoon trough in July and August (Srinivasan et al., 1972 and Pathan, 1993). The northern most part of these states are sub-mountainous. The monsoon rainfall over these states mainly depends on the activity of the monsoon trough. The common synoptic situation that produce good rainfall in Bihar and UP includes low pressure system and upper air cyclonic circulation over the region and neighborhood, monsoon trough across the region, north south orientated trough in the monsoon westerly or a westerly trough moving across the western Himalayas or Tibet in the upper troposphere (Srinivasan et al., 1972). In association with the above synoptic situations, UP and Bihar experiences floods due to heavy rainfall during main monsoon month of July and August. Rainfall, even of the order of 30-40 cm in 24 hours has occurred in UP, the amount being as high as 50 cm in south east UP, while the amount of the order of 40-50 cm has also been reported in Bihar (Srinivasan et al., 1972).

The prediction of heavy rainfall over Bihar and UP is still challenging for the forecasters in spite of advances in numerical weather prediction (NWP). The performance of 24 hours heavy rainfall warnings issued by India Meteorological Department (IMD) during recent 5 years (2001-2005) have been analysed and discussed by Mohapatra et al., (2009). They have shown that the performance of 24 hours heavy rainfall warning over these regions needs significant improvement as the percentage correct is about 70 -80% and probability of detection of heavy rainfall is 50-60% with the false alarm rate of 60-80% and missing rate is 35-45%. It may be due to the facts that synoptic meteorologists have always given very high credence to the synoptic conditions while issuing these warnings. In addition, the poor performance may be due to the subjectivity involved in the present method of heavy rainfall warning, which largely depends on the expertise/ability of decision making of the forecaster.

The analysis of the synoptic systems associated with the unanticipated heavy rainfall events over UP and Bihar suggests that proper weightage to (i) the small scale systems like low level cyclonic circulation over the region and neighborhood, (ii) the interaction of the mid-latitude westerlies with the monsoon systems and (iii) the northward sloping of monsoon trough embedded with low pressure system/cyclonic circulation(LPSC) to the immediate south of the region along with the use of advanced NWP models can immediately help in improving the warning skill (Mohapatra et al., 2009). Review of past studies indicate that when the monsoon trough shifts northward of its normal position these areas become the wind ward slope of the Himalaya. Studies by Sarkar (1966, 1967) and De (1973) indicate that in addition to forced orographic ascent and synoptic scale convergence, convective instability is also a very important factor for heavy to very heavy precipitation on the wind ward slope. There is a need for quantification of mesoscale forcing of convection and hence identification of precursors for heavy rainfall over Bihar and UP. The mesoscale convection over a region can be analysed and interpreted in terms of the thermodynamical features including instability indices. Dutta and De (1999) studied convective instability during contrasting rainfall epochs over Mumbai. It was shown that in most cases, the days with higher precipitation were associated with higher values of Convective Available Potential Energy (CAPE). De and Dutta (2005) considering the role of convective instability in producing heavy rain over windward side of Western Ghat, have shown that the heavy rainfall is associated with a rise in positive value of CAPE and fall in negative value of Convective Inhibition Energy (CINE). However, such studies relating thermodynamic indices and heavy rainfall over Bihar and UP are limited.

Considering all the above, this study has been undertaken to analyze the thermodynamic characteristics associated with heavy rainfall over UP and Bihar and to find the possible predictors based on the data of 5 years from 2001 to 2005. The results of this study can be used for day to day forecasting apart from yielding a scientific understanding of the relationship between thermodynamical parameters and occurrence of heavy rainfall.

2. Data and Methodology

As per the criteria of IMD, it is said to be heavy rainfall over a station if the 24 hrs cumulative rainfall at 0830 hrs IST over the station is 64.5 mm or more. The same criteria have been applied to identify the heavy rainfall events over the three subdivisions of Bihar, East UP and west UP (Figure 1). To avoid the isolated heavy rainfall events

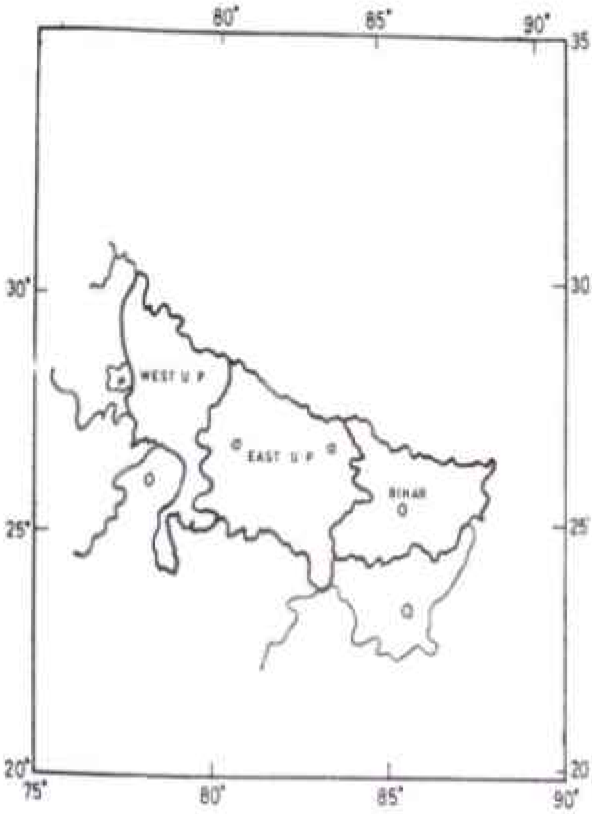

Figure 1: Region of study under consideration and the RS/RW stations from which 0000UTC observations are used.

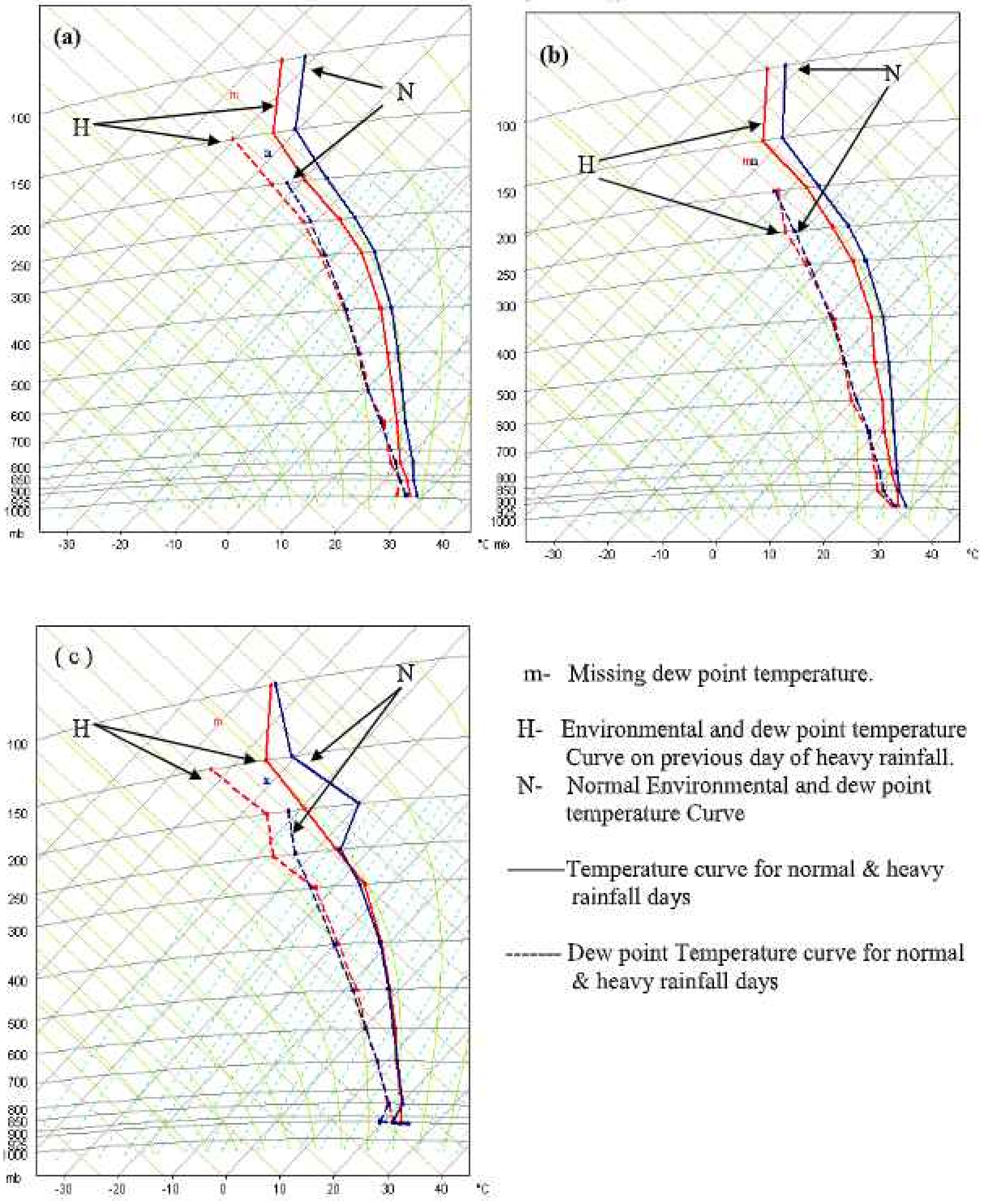

Figure 2: Thermodynamic Characteristics over (a) Gorakhpur (b) Patna and (c) Ranchi associated with heavy rainfall over Bihar.

due to mesoscale convection, it has been considered as a heavy rainfall day over subdivision if at least two stations in that subdivision recorded heavy rainfall. As July and August are main monsoon months and most of the heavy rainfall events occur over Bihar and UP during these two months, the heavy rainfall events of these two months during 2001-2005 have been considered for the detailed study of their relationship with thermodynamical features. The mean frequency of heavy rainfall events over these subdivisions during July and August are shown in Table 1.

Table 1. Number of heavy rainfall days (D) and the number of days of data available on Previous Day of heavy rainfall (PD) over Bihar, E-UP and W-UP.(PTN-Patna, RNC-Ranchi, GRK-Gorakhpur, LKN-Lucknow, DLH-Delhi, GWL-Gwalior)

	Bihar			E-UP			W-UP		
	PTN	RNC	GRK	GRK	LKN	PTN	LKN	DLH	GWL
PD	65	61	51	72	86	80	32	32	24
D	82	82	82	102	102	102	38	38	38

Table 2. Thermodynamic parameters considered in the study associated with heavy rainfall over Bihar and UP.

SN	Parameter
1	Temperature(^{0}C) at 925, 850,700,600,500,400,300,250,200 hPa levels
2	Dew point (^{0}C) at 925, 850,700,600,500,400,300,250,200 hPa levels
3	Relative Humidity(%) at 925, 850,700,600,500,400,300,250,200 hPa levels
4	Convective available potential Energy (J/Kg)
5	Convective Inhibitions Energy (J/Kg)
6	Kinetic factor
7	Bulk Richardson Number
8	Temperature [k] of Lifting Condensation Level
9	Pres [hPa] of Lifting Condensation Level
10	Precipitable water (mm)
11	Equilibrium level (hPa)
12	Level of Free Convection (LFC) (hPa)
13	Showalter index(SI)
14	Lifted index(LI)
15	K- index(KI)
16	SWEAT index
17	Cross totals index(CTI),
18	Vertical totals index(VTI
19	Total totals index(TTI)

The thermodynamic parameters under consideration are shown in Table 2. It includes the basic parameters like Environmental Temperature, Dew Point and Relative Humidity at surface and different standard isobaric levels. Further, the derived parameters like the thermodynamical indices and the parameters derived from the Tephigram of the station influencing the rainfall over these three subdivisions are considered. All the available radiosonde stations of IMD in and around the meteorological subdivisions have been considered in the study. The raidosonde data at 0000 UTC for the period 2001-2005 have been collected from IMD stations (Figure 1). For the analysis purpose, the raidosonde data at 0000UTC of the day prior to the recording of heavy rainfall over the subdivision have been considered. The number of days of heavy rainfall for which RS data are available are shown in Table 1. To examine the relation between occurrence of heavy rainfall over a subdivision and the thermodynamic parameters, the radiosonde and radiowind (RS/RW) data from the stations in and around that subdivision have been considered. Hence for heavy rainfall over Bihar, RS/RW data for Patna (PTN), Gorakhpur (GRK) and Ranch (RNC) are considered. Similarly RS/RW data of Lucknow (LKN), GRK and PTN are considered for heavy rainfall over east UP and of Gwalior (GWL), Delhi (DLH) and LKN are considered for heavy rainfall over west UP.

The list of thermodynamic parameters and indices is given in Table 2. Various thermodynamic indices including Showalter index (SI), lifted index (LI), sweat index, K-index (KI), cross totals index (CTI), vertical totals index (VTI), total totals index (TTI), convective available potential energy (CAPE), convective inhibitions energy (CINE), bulk Richardson number (BRN), Temperature [k] of lifting condensation level (LCL), Pressure [hPa] of LCL, precipitable water, equilibrium level and level of free convection (LFC) etc. have been calculated and analysed. The details of methods of calculation of various indices are discussed in Section 2.1.

Mean value along with standard deviation of various thermodynamic parameters and indices on the previous day of recording of heavy rainfall have been calculated and analyzed. Further, these mean values have been compared to the long term mean values based on the climatological data prepared by IMD. To find out the significant difference, if any, in the value of different parameters and indices during heavy rainfall from the climatological values, the student 't'-test has been applied. Statistically significant results have been presented and analysed here. The mean Tephigram associated with heavy rainfall events and the Tephigram based on climatological data have also been plotted and analysed to find out instability characteristics associated with heavy rainfall events.

2.1 Thermodynamic indices

Method of calculation of various indices are given below following http://weather.uwyo.edu/ upperair/ indices.html and Anantha krishnan & Yegna narayanan (1949).

(i) Temperature [k] of LCL

(ii) Pressure [hPa] of LCL

(iii) Level of free convection (LFC)=Level at which a parcel from the lowest 500m of atmosphere is raised dry adiabatically to LCL and moist adiabatically to a level above which the parcel is positively buoyant. If more than one LFC exists, the lowest level is chosen.

(iv) Equilibrium level(EQLV)= Level at which a parcel from the lowest 500m of the atmosphere is raised dry adiabatically to the LCL and moist adiabatically to a level above which the temperature of the parcel is the same as the environment. If more than one equilibrium level exists, the highest one is chosen.

(v) Convective available potential energy(CAPE)
CAPE =GRAVITY*SUMP*{DELZ*(TP-TE)/TE}
SUMP= Sum over sounding layers from LFC to EQLV for which (TP-TE)>0
DELZ=Incremental depth
TP=Temp. of the parcel from the lowest 500m of the atmosphere, raised dry adiabatically to the LCL & moist adiabatically thereafter.
TE= Temp. of the environment.

(vi) Convective inhibitions energy(CINE)= GRAVITY*SUMN*{DELZ*(TP-TE)/TE}
SUMN= Sum over sounding layers from top of the mixed layer to LFC for which (TP-TE)<0, DELZ=Incremental depth, TP=Temp. of the parcel from the lowest 500m of the atmosphere, raised dry adiabatically to the LCL & moist adiabatically thereafter. TE= Temp. of the environment.

(vii) Precipitable water (mm)

(viii) Showalter index(SI) = T_{500}-T_{P500}
T_{500}=Temperature in Celsius at 500hPa
T_{P500}=Temperature in Celsius at 500hPa of parcel lifted dry adiabatically from 850hPa to 500hPa.

(ix) Lifted index(LI)= T_{500}-T_{Parcel}
T_{500} – Temperature in Celsius of the environment at 500hPa. T_{Parcel} – 500hPa temperature in Celsius of a lifted parcel with the average pressure temperature and dew point of the layer 500m above the surface to 500hPa

(x) K- index(KI) = (T_{850}-T_{500}) + Td_{850}-(T_{700}-Td_{700})
T_{850}= Temperature in Celsius at 850hPa
Td_{850}= Temperature in Celsius at 500hPa
Td_{850}= Dew point in Celsius at 850hPa
T_{700}= Temperature in Celsius at 700hPa
Td_{700}= Dew point in Celsius at 700hPa

(xi) Cross totals index(CTI)= Td_{850}- T_{500}
Td_{850}= Dew point in Celsius at 850hPa
T_{500} – Temperature in Celsius at 500hPa

(xii) Vertical totals index(VTI)= T_{850}- T_{500}
T_{850}= Temperature in Celsius at 850hPa

T_{500} - Temperature in Celsius at 500hPa

(xiii) Total totals index(TTI)=(Td_{850}- T_{500})+(T_{850}-T_{500})
Td_{850}= Dew point in Celsius at 850hPa
T_{500} - Temperature in Celsius at 500hPa
T_{850}= Temperature in Celsius at 850hPa

(xiv) SWEAT
index=12*Td_{850}+20*Term2+2*SKT_{850}+SKT_{500}+Shear
Td_{850}= Dew point in Celsius at 850hPa
Term2=Max(TTI-49.0)
TTI =Total totals index
SKT_{850}=850hpa wind speed in knots
SKT_{500}=500hpa wind speed in knots
Shear=125[Sin(Dir500-Dir850)+0.2]

(xv)Bulk Richardson Number(BRN)=CAPE/(0.5*U**2)
CAPE=Convective available potential Energy
U=Magnitude of shear (u2-u1, v2-v1)
u1v1=Average u, v in the lowest 500m
u2v2= Average u, v in the lowest 6000m

(xvi) Kinetic factor=(|CAPE|-|CINE|)/|CINE|

3. Results and Discussion

Thermodynamic characteristics associated with heavy rainfall over Bihar, east UP and west UP are presented and discussed in Section 3.1, 3.2 and 3.3 respectively. The broad conclusions of the study are presented in Section 4.

3.1 Thermodynamic characteristics associated with heavy rainfall over Bihar

The mean Tephigrams of Gorakhpur, Patna and Ranchi located in and around Bihar (Figure 2), indicate that the atmosphere is heavily unstable over all the stations under consideration. It endorses the earlier finding of Rao et al. (1970), that the atmosphere is unstable over UP and Bihar during main monsoon months. The results also endorse the fact that the moisture contents are usually higher over these regions in the lower and middle troposphere.

However, prior to the occurrence of heavy rainfall, the environmental temperature is less than normal by about 2-3^{0}C at all levels of troposphere over Patna and Gorakhpur. However, dew point remains same as normal. Hence, the relative humidity prior to the occurrence of heavy rainfall significantly increases both in magnitude and vertical depth. The RH is higher than the normal by 10-15% at 700-400 hPa levels over Patna and Gorakhpur. The rise is relatively less over Ranchi (5-10%). The RH is maximum over Gorakhpur among the three stations up to 250 hPa level. Also the Tephigrams indicates that the atmosphere becomes more unstable over Bihar and surroundings prior to occurrence of heavy rainfall. The Tephigram over Ranchi does not indicate any significant difference associated with the heavy rainfall over Bihar from normal pattern. It may be due to the fact that the heavy rainfall over Bihar mainly occurs in association with monsoon trough/seasonal trough running over this region with/without embedded cyclonic circulation/low pressure system (Mohapatra et.al., 2009). Monsoon trough shifts to Bihar region in association with all India weak monsoon condition (Rao,1976). This synoptic environment leads to more instability and increased moisture availability over Bihar. At the same time, the condition becomes unfavourable leading to more stability over Ranchi as the monsoon trough lies far north of Ranchi. The mean climatological environmental temperature and dew point at different standard isobaric levels from 925hPa to 200hPa along with those associated with heavy rainfall over Bihar are presented in Table 3. The results presented in Table 3 also confirm the above findings.

The mean thermo–dynamical indices along with those associated with heavy rainfall over Bihar are shown in Table 3. Thus the thermo-dynamical indices (Table 4) significantly higher than normal values of KI, TTI, VTI, CTI & sweat index over Patna and significantly less than normal LI are favourable for heavy rainfall over Bihar. The indices over Ranchi and Gorakhpur are not significantly related with occurrence of heavy rainfall over Bihar except that higher than normal sweat index over these two stations and high SI over Ranchi favour heavy rainfall over Bihar. Hence, RS/RW data of Patna is very crucial for prediction of occurrence of heavy rainfall over Bihar during next 24hours as most of the thermo-dynamical indices of this station are significantly related with the occurrence of heavy rainfall over Bihar. The Sweat index which is directly related

Table 3. Mean temperature (^{0}C), Dew point (^{0}C), Relative humidity (%) and their difference from normal values over different stations associated with heavy rainfall over Bihar.

M indicates Mean temperature and D is the Difference from normal (Mean-Normal). The temperatures which are significantly different from the normal values are shown in bold.

Levels hPa	Patna						Ranchi						Gorakhpur					
	Temperature (°C)		Dew point (°C)		RH(%)		Temperature (°C)		Dew point (°C)		RH(%)		Temperature (°C)		Dew point (°C)		RH(%)	
	M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D
925	24.4	-0.4	20.8	-1.1	83	-1	23.5	1.9	22.2	3.0	93	7	24.3	-1.2	22.9	0.1	93	8
850	20.2	-0.9	17.1	-0.9	85	3	20.2	-0.2	17.6	-0.2	87	2	19.5	-2.5	17.8	-0.9	91	9
700	11.3	-1.3	8.4	-0.1	84	10	11.8	-0.1	8.3	0.1	82	5	11.5	-1.7	9.1	0.5	87	13
600	5.2	-1.7	-0.5	-1.0	70	6	5.7	0.3	0.4	0.1	72	2	5.0	-1.7	0.5	0.1	76	12
500	-2.9	-2.4	-8.3	-0.1	69	14	-2.1	0.2	-7.9	0.8	69	8	-2.7	-1.9	-7.6	-0.4	73	15
400	-11.7	-2.1	-18.3	0.5	61	14	-11.7	0.3	-19.3	0.7	59	8	-12.2	-1.9	-18.5	-0.2	63	11
300	-25.3	-2.2	-33.4	-0.6	50	9	-25.0	0.8	-33.5	0.8	50	5	-25.8	-2.2	-32.9	-0.7	56	5
250	-35.1	-2.6	-43.1	-1.5	46	6	-36.2	-0.6	-46.9	-3.7	38	-8	-36.0	-2.7	-42.1	-1.2	55	9
200	-47.1	-1.9	-51.9	0.6	50	6	-49.1	-9.1	-55.3	-3.4	50	23	-49.4	-3.6	-54.9	-2.5	49	2

with wind shear in lower to middle levels, wind speed at lower levels, temperature and dew point in lower and middle levels take into consideration all the dynamical, thermal and moisture factors. Hence, the favourable sweat indices over all the three stations indicate favourable environmental features over the region.

Considering the CAPE and CINE (Table 5), CAPE > 1900J/Kg over Patna and > 1700 J/Kg over Gorakhpur with CINE < 30 J/Kg and < 50 J/Kg respectively. The BRN which is directly related with CAPE and inversely related with magnitude of wind shear between middle and lower levels is significantly higher over Patna (1643). The LCL lies around 930-935hPa for Patna and Gorakhpur and at relatively higher level over Ranchi with the temperature of 23-24^{0}C over Patna and Gorakhpur and 21^{0}C over Ranchi. The LFC is lowest over Patna (865hPa) followed by Gorakhpur (822hPa) with equilibrium level of 200hPa and 244hPa respectively. These indicates again that heavy rainfall over Bihar is associated with favourable indices over Patna followed by Gorakhpur.

3.2 Thermodynamic characteristics associated with heavy rainfall over east UP

The mean tephigram over Gorakhpur, Lucknow and Patna associated with heavy rainfall over east UP are presented in Figure 3. It is found that the environmental temperature is less than normal by 2-3^{0}C over Gorakhpur and Patna at 0000UTC of day of occurrence of heavy rainfall over east UP while dew point slightly decreases over Gorakhpur and remains almost same over Patna. It indicates that the atmosphere becomes more saturated and hence there is increase in RH over these stations. On the other hand, both dew point and environmental temperature increase over Lucknow. The rise in dew point is relatively more than resulting in rise in RH. Hence the region of UP lying to east becomes more favourable for the occurrence of heavy rainfall in these situations. Further, the synoptic system like low pressure systems move west-northwestward along the monsoon trough (Rao,1976) and accordingly the zone of convection and the heavy rainfall shift west-northwestwards. The above characteristics of temperature, dew point and RH are further illustrated in Table 6. The RH over Gorakhpur is maximum among three stations in all levels under consideration. The RH over Gorakhpur is higher than the normal by 10-20% in all levels of troposphere while it is so only in middle troposphere in case of Lucknow and Patna. Hence, the RS/RW data of Gorakhpur plays major role for prediction of heavy rainfall over east UP.

Table 4. Mean values of indices during Normal days (N) and heavy rainfall days (H) over Bihar and UP.(PTN-Patna, RNC-Ranchi, GRK-Gorakhpur, LKN-Lucknow, DLH-Delhi, GWL-Gwalior)

Indices	Bihar					
	PTN		RNC		GRK	
	N	H	N	H	N	H
SI	-1.1	-0.7	-8.3	**-0.5**	-1.8	-0.9
KI	35	**37.8**	43.2	37	36.9	-37.5
LI	-1.1	**-3.3**	-8.3	-1.5	-1.8	-3.5
TTI	40.1	**43.1**	42.8	42.2	42.3	42.7
VTI	21.6	**23**	22.7	22.3	22.8	22.2
CTI	18.5	**20**	20.1	20	19.5	20.5
SWEAT INDEX	80	**263**	122.6	**243.6**	132.4	**277.2**
East-UP						
Indices	GRK		LKN		PTN	
	N	H	N	H	N	H
SI	-1.8	-1.7	-3.1	-2	-1.1	-0.4
KI	36.9	38.1	37.2	39.1	35	**37.4**
LI	-1.8	-3.8	-3.1	-3.9	-1.1	-3.2
TTI	42.3	**44.7**	44	44.5	40.1	**42.1**
VTI	22.8	23.2	23.6	23.4	21.6	**22.3**
CTI	19.5	**21.5**	20.4	21.1	18.5	**19.9**
SWEAT INDEX	132.4	**277.6**	153.2	**274.5**	80	**248.6**
West-UP						
Indices	LKN		DLH		GWL	
	N	H	N	H	N	H
SI	-3.1	-1.7	-2.9	**1.1**	-1.5	-3.7
KI	37.2	39.4	37.5	33.6	36.3	**42.2**
LI	-3.1	-3.4	-2.9	-1.0	-1.5	-4.9
TTI	44	43.7	44.4	40.2	42.1	**47.2**
VTI	23.6	23	24.2	21.5	23.1	**24.5**
CTI	20.4	20.7	20.2	18.7	19	**22.7**
SWEAT INDEX	153.2	**257**	159.4	**236.1**	115.4	**287.2**

Thus the thermo-dynamical indices significantly higher than normal values of TTI and CTI over Gorakhpur, higher than normal values of TTI, VTI, CTI, KI over Patna and sweat index all over the three stations are favourable for the occurrence of heavy rainfall over east UP (Table 4)

Considering the instability parameters like CAPE and CINE (Table 5), CAPE is almost same (~1900J/Kg) far all the three stations under consideration with CINE ranging between 20-60J/Kg. The LCL lies between 930-940 hPa with temperature of 23-24^{0}C over all the three stations. The LFC lies between 830-890 hPa with equilibrium level being around 200 hPa. Hence, the parameters mentioned in Table 5 for heavy rainfall over east UP do not show unique relationship for any given RS/RW stations except the Bulk Richardson number, though heavy rainfall over east UP is associated with desired higher values of CAPE, equilibrium level, lower value of CINE, LFC and LCL over the region. Higher Bulk Richardson number over Lucknow(value of 2875) favours heavy rainfall over east UP.

3.3 Thermodynamic characteristics associated with heavy rainfall over west UP

The mean tephigram over Gwalior, Lucknow and Delhi representing the heavy rainfall characteristics over west UP are shown in fig.4. While the environmental temperature is less than normal, the dew point is higher than normal over Gwalior at 0000UTC of day of occurrence of heavy rainfall over west UP. It clearly indicates significant increase in moisture and hence RH over Gwalior on such occasions in all levels extending upto upper troposphere. On the other hand, while the dew point increases, the environmental temperature also increases over Lucknow which lies in east UP. Hence the margin of increase in RH over the normal is relatively less and it is upto mid-tropospheric level (400hPa). Considering Delhi, there is no significant difference in temperature and dew point compared to the normal except that dew point decreases in upper troposphere. The higher than normal RH is limited upto 500hPa. RH is maximum at all the levels under consideration over Gwalior among three stations. All these results are

Table 5. Mean values of CAPE, CINE, Bulk Richardson number, Temperature and Pressure of LCL Equilibrium level associated with heavy rainfall over Bihar and UP. (PTN-Patna, RNC-Ranchi, GRK-Gorakhpur, LKN-Lucknow, DLH-Delhi, GWL-Gwalior)

Indices	Bihar			East UP			West UP		
	PTN	RNC	GRK	GRK	LKN	PTN	LKN	DLH	GWL
CAPE(J/Kg)	1922.5	1159.7	1741.3	1908.7	1967.7	1907.8	2298.1	1607.1	2810.9
CINE(J/Kg)	-28.9	-40.1	-45.7	-40.3	-61.1	-20.9	-91.3	-49.7	-59.6
Kinetic factor	65.5	27.9	37.1	46.4	31.2	90.3	24.2	31.3	46.2
Bulk Richardson No.	1642.5	568.7	751.7	1573.9	2876.2	1668.4	2080.9	1177.0	1351.5
Temp [K] of LCL	296.3	293.7	296.7	296.4	297.2	296.9	297.2	294.2	296.9
Pres [hPa] of LCL	932.9	882.0	935.1	937.9	932.8	941.4	931.2	905.8	920.6
Precipitable water (mm)	65.4	54.6	70.8	65.5	71.9	66.4	77.0	58.4	68.2
Equilibrium Level (hPa)	200.3	178.4	244.1	225.6	195.8	192.4	186.0	206.9	134.8
LFC (hPa)	865.4	785.7	821.6	832.0	835.3	884.1	802.0	818.2	804.4

Table 6. Mean temperature (^{0}C), Dew point (^{0}C), Relative Humidity (%) and their difference from normal values over different stations associated with heavy rainfall over East UP.
M indicates Mean temperature and D is the Difference from normal (Mean-Normal). The temperatures which are significantly different from the normal values are shown in bold.

Levels hPa	Gorakhpur						Lucknow						Patna					
	Temperature (^{0}C)		Dew point (^{0}C)		RH(%)		Temperature (^{0}C)		Dew point (^{0}C)		RH(%)		Temperature (^{0}C)		Dew point (^{0}C)		RH(%)	
	M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D
925	23.6	-1.9	22.3	-0.5	93	8	25.2	0.4	23.1	0.8	89	3	24.0	-0.8	21.4	-0.4	87	3
850	19.7	-2.3	17.9	-0.8	92	10	21.3	0.5	19.0	1.4	88	6	19.9	-1.2	17.5	-0.5	88	6
700	10.5	-2.7	7.5	-1.1	84	10	12.7	1.1	9.4	1.8	83	7	11.4	-1.7	8.7	0.2	85	11
600	3.9	-2.8	-0.3	-0.7	77	13	6.6	1.6	2.5	1.5	77	12	5.3	-1.6	-0.1	0.6	71	7
500	-3.5	-2.7	-8.2	-0.2	74	16	2.1	4.9	-8.5	1.0	69	9	-2.4	-1.9	-7.7	0.5	70	14
400	-13.0	-2.7	-19.1	-0.8	64	12	-11.5	1.2	-17.5	3.1	63	11	-12.0	-2.4	-18.7	0.1	62	15
300	-26.6	-3.0	-33.9	-1.7	55	10	-24.6	2.5	-33.3	2.4	50	6	-25.5	-2.4	-33.1	-0.8	52	11
250	-36.0	-2.7	-41.8	-0.9	56	10	-33.5	3.8	-42.5	2.4	47	2	-35.3	-2.8	-42.5	-0.9	49	9
200	-49.4	-3.6	-53.8	-1.4	69	22	-46.2	6.1	-50.8	5.2	51	0	-48.4	-3.2	-53.6	-1.1	51	7

quantitavely shown in Table 7. From the Table 7, the RH is higher than normal by about 10-20% in all levels of the troposphere over Gwalior. It is 10-13% only in middle troposphere in case of Lucknow and Delhi. Further there is decrease in RH by 10-15%in the upper troposphere over Delhi and at 200hPa level over Lucknow. Considering all the above, Gwalior is more representative of thermodynamic characteristics associated with heavy rainfall over west UP and thermodynamic

Table.7 Mean temperature (^{0}C), Dew point (^{0}C), Relative Humidity (%) and their difference from normal values over different stations associated with heavy rainfall over West UP.
M indicates Mean temperature and D is the Difference from normal (Mean-Normal). The temperatures which are significantly different from the normal values are shown in bold.

Levels hPa	Lucknow						Delhi						Gwalior					
	Temperature (^{0}C)		Dew point (^{0}C)		RH(%)		Temperature (^{0}C)		Dew point (^{0}C)		RH(%)		Temperature (^{0}C)		Dew point (^{0}C)		RH(%)	
	M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D
925	25.2	0.4	23.0	0.7	88	2	24.7	-0.9	21.5	-0.1	83	4	25.5	0.0	23.4	1.8	89	10
850	21.4	0.6	19.2	1.6	88	6	19.2	-2.5	16.7	-1.1	86	8	21.5	-0.3	19.5	1.8	89	11
700	12.6	1.0	9.9	2.3	84	8	11.1	-0.9	6.8	-0.8	81	7	11.6	-1.1	9.7	1.5	89	15
600	7.5	2.5	3.2	2.2	77	12	5.3	0.2	0.2	1.2	73	10	5.3	-0.9	1.4	1.8	79	16
500	-1.6	1.2	-6.5	3.0	73	13	-2.2	0.3	-8.7	0.9	68	10	-3.0	-1.7	-7.8	0.5	73	14
400	-11.1	1.6	-18.3	1.7	61	9	-11.9	0.0	-22.5	-2.1	48	-1	-13.0	2.7	-18.6	-0.2	65	14
300	-25.3	1.8	-35.7	0.0	45	1	-25.8	0.2	-38.9	-4.3	36	-8	-27.5	-4.8	-35.4	-3.2	51	6
250	-35.8	1.5	-44.5	0.4	45	0	-33.2	0.7	-48.5	-5.1	32	-14	-37.7	-4.4	-44.2	0.3	50	18
200	-46.7	3.6	-52.1	3.1	42	-9	-48.5	0.2	-60.0	-4.5	28	-15	-51.5	-5.8	-61.4		38	

parameters over Gwalior can be used for prediction of heavy rainfall over west UP.

Considering the thermodynamic indices (Table 4), the significantly higher than normal KI, TTI, VTI, CTI over Gwalior and higher than sweat index over all the three stations at 0000UTC of the day are favorable for occurrence of heavy rainfall over west UP during next 24hours.

Considering the CAPE and CINE (Table 5), CAPE is maximum for Gwalior (>2800J/Kg) with a CINE of about 60J/Kg.The LCL lies between 905-930hPa with the temperature of 21-24^{0}C. The LFC is about 800-820hPa with equilibrium level of 200hPa and above. The equilibrium level is higher over Gwalior (135hPa). The BRN is maximum over Lucknow followed by Gwalior. Like heavy rainfall over east UP, the heavy rainfall over west UP is not dominantly associated with the parameter mentioned in Table 5 for a single RS/RW station.

Considering the indices associated with heavy rainfall over three sub divisions, equilibrium levels in all the cases is about 200hPa or above. The LFC lies between 850 and 800hPa levels. The LCL lies between 950 and 900hPa levels with temperature of 21-24^{0}C. The precipitable water is more than50 mm. The CAPE is higher in case of heavy rainfall over west UP compared to that of east UP and Bihar. The CINE varies between 20 to 60J/kg in all the three subdivisions.

4. Conclusions

The following broad conclusions are drawn from the study.

(i) The thermodynamic parameters at 0000UTC of the day can be used for prediction of occurrence of heavy rainfall over Bihar, east UP and west UP during the next 24 hours. Significantly higher than normal sweat index over the region indicating favorable environmental condition is associated with heavy rainfall over Bihar and UP.

(ii) While the heavy rainfall over Bihar and west UP are uniquely related with higher than normal thermodynamic indices KI, TTI, VTI and CTI over Patna and Gwalior respectively, the heavy rainfall over east UP is related with higher than normal TTI and CTI over Gorakhpur and KI, TTI, VTI and CTI over Patna.

(iii) Above normal relative humidity by 10-15% at different levels up to the troposphere over Patna, Gorakhpur and Gwalior stations favours occurrence of heavy rainfall over Bihar, east UP and west UP respectively.

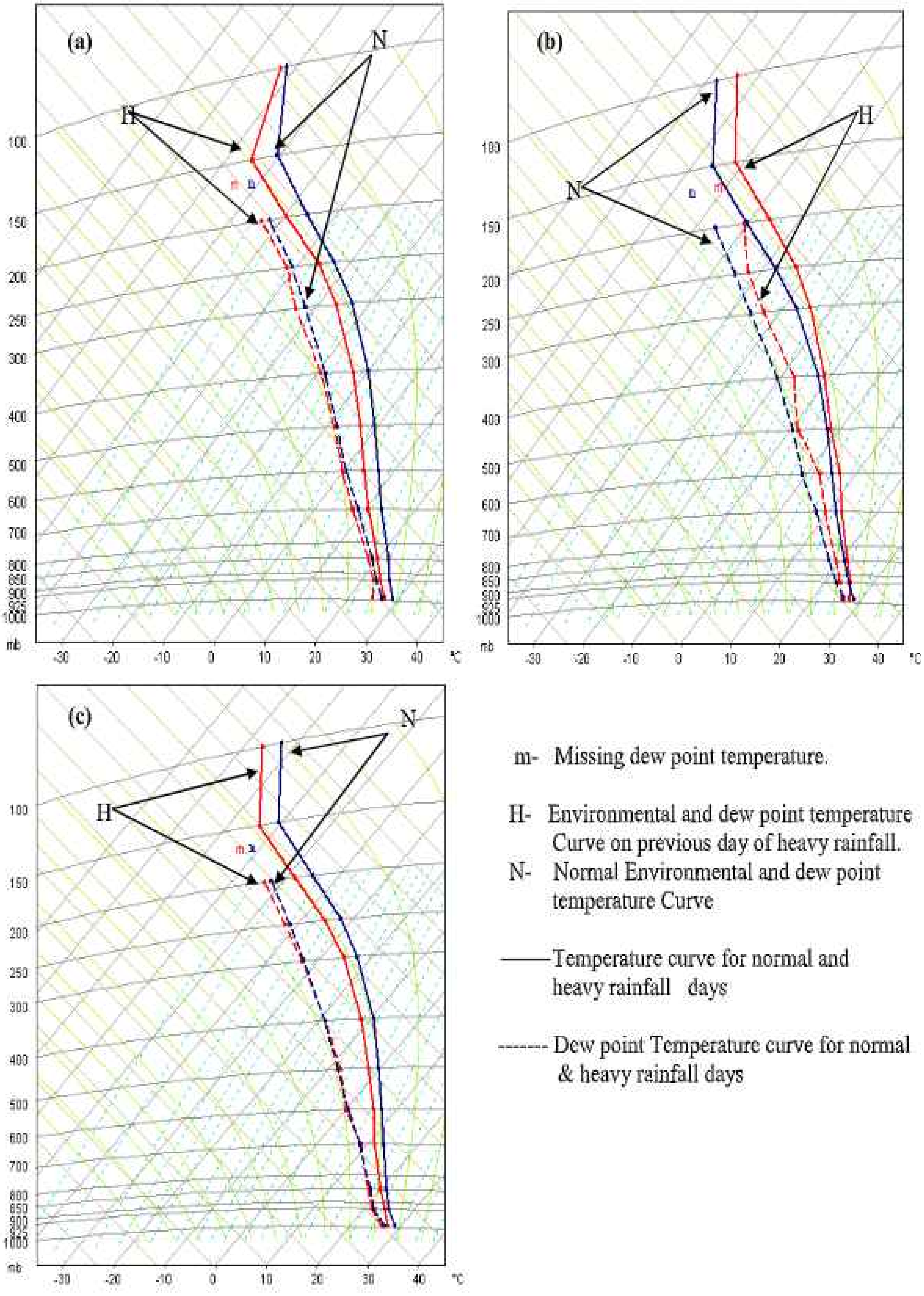

Figure 3: Thermodynamic Characteristics over (a) Gorakhpur (b) Lucknow & (c) Patna associated with heavy rainfall over East-UP.

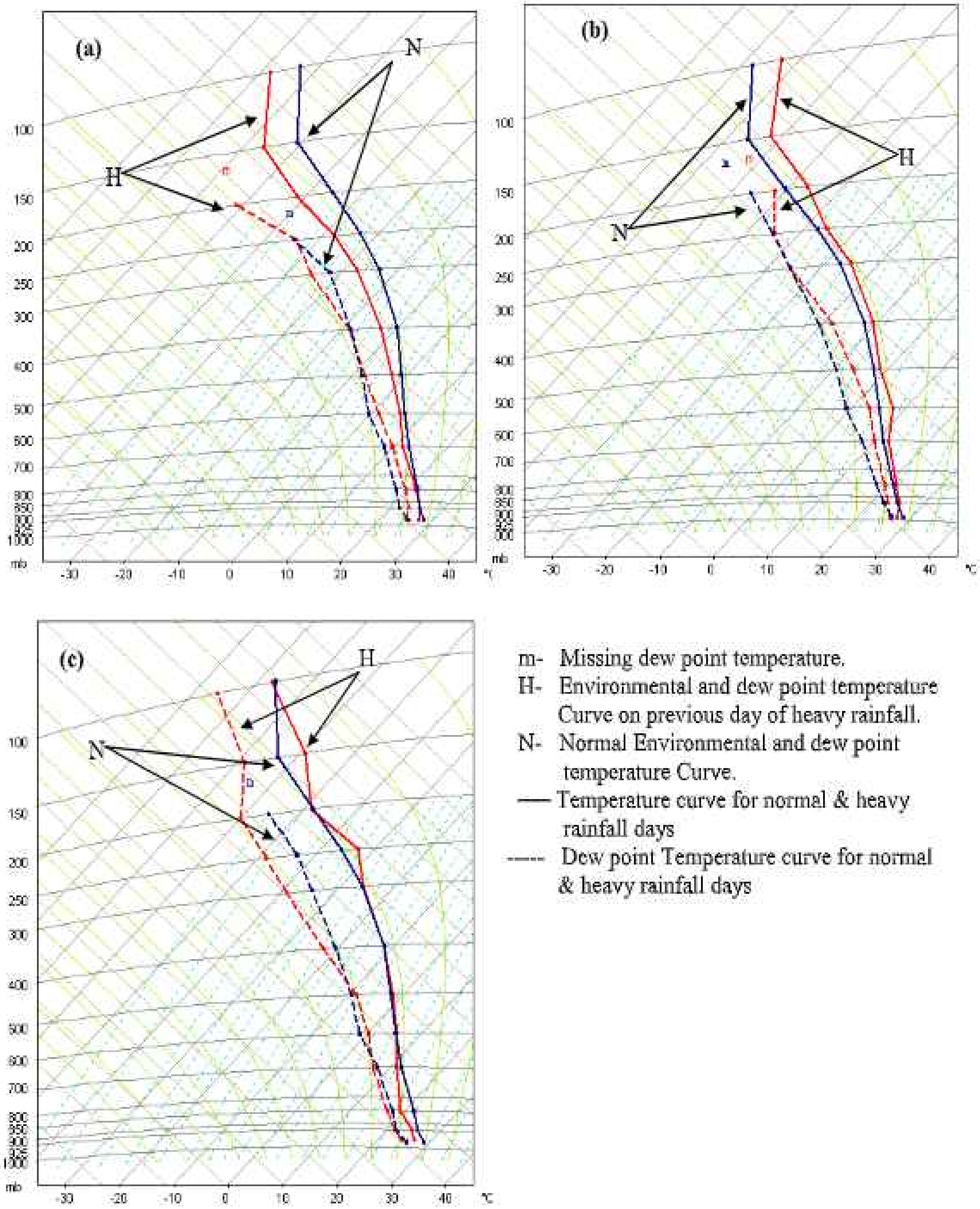

Figure 4: Thermodynamic Characteristics over (a) Gwalior (b) Lucknow & (c) Delhi associated with heavy rainfall over West-UP.

(iv) The lifting condensation level lies between 950 and 900hPa levels over Patna, Gorakhpur and Gwalior with temperature of LCL lying between 20-24^{0}C for occurrence of heavy rainfall over Bihar, east UP and west UP respectively. While the LFC for these stations are between 800-850hPa, the equilibrium level lies above 200hPa for occurrence of heavy rainfall.

(v) The mean CAPE associated with heavy rainfall over Bihar is greater than 1900J/Kg over Patna. The heavy rainfall over east UP is associated with mean CAPE of greater than 1900J/Kg over Gorakhpur and heavy rainfall over west UP is associated with mean CAPE of greater than 2800 J/Kg over Gwalior respectively. The CINE less than 30J/Kg, 40 J/Kg, 60 J/Kg over Patna, Gorakhpur and Gwalior are associated with heavy rain fall over Bihar, east UP and west UP respectively. While Patna and Gwalior have uniquely higher values of CAPE and kinetic factor for heavy rainfall over Bihar and west UP respectively. Gorakhpur does not exhibit so for heavy rainfall over east UP.

(vi) The precipitable water ranges between 55-70, 66-70 and 60-80 mm for the occurrence of heavy rainfall over Bihar, east UP and west UP respectively.

References

Ananthakrishnan and Yegnanarayanan, S., 1949, "Interpretation of Tephigramm" Technical note No 26, India Meteorological Department.

De, U.S. and Dutta, Somnath, 2005, "West coast rainfall and convective instability", J. Ind. Geophysics Union, 9, 71-82.

Dutta, S.N. and De,U.S.,1999, "A diagnostic study of contrasting rainfall epochs over Mumbai", Mausam, 50, 1-8.

Mohapatra, M., Hatwar,H.R. and Kalsi,S.R.,2009, "Verification of heavy rainfall over Bihar and Uttar Pradesh", Mausam, 60, 2, 175-180.

Pathan, J. M., 1993, "Latitudinal variation of rainfall during the month of July in relation to the Axis of monsoon trough over India", Mausam, 44, 384-386.

Rao, Y. P., 1976, " The South west monsoon, Met Monograph" India Meteorological Department, Pune.

Sarkar, R. P., 1966, "A dynamical model of orographic rainfall", Monsoon, weather, Review 94, 555-572.

Sarkar, R. P., 1967, "Some modification in a dynamical model of orographic rainfall", Monsoon, Weather, Review, **95** 673-684.

Sikka, D. R.,1980, "Some aspect of the large scale fluctuation of summer monsoon rainfall over India in relation to fluctuation in the planetary and regional scale circulation parameters", Pro. Indian Acad. Sci.(Earth and Planetary sciences),89,179-195.

Srinivasan, V., Raman, S. and Mukherjee, S., 1972, "Southwest monsoon –Typical synoptic situations over Uttar Pradesh and Bihar States", IMD, *FMU Rep*. No III-3.5, 1-75.