Characteristics of ABL during active and weak phases of monsoon

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ABSTRACT

Understanding of the Atmospheric Boundary Layer (ABL) is imperative in the arena of the monsoon field. Here, the features of the ABL are studied employing Conserved Variable Analysis (CVA) using equivalent potential temperature and humidity. In addition, virtual potential temperature and wind are used during active and weak phases of monsoon. The analysis is carried out utilising the radiosonde observations during the monsoon months for two stations situated in the west coast of India. All these parameters show considerable variations during active and weak monsoon phases in both the stations. The core speed and core height vary with these epochs. The core speed is found to be more than 38 knots in the active monsoon phase around 1.2 km over Trivandrum and around 2 km over Mangalore. But during weak monsoon phase the core wind speed is decreased and core height is elevated over both stations. The wind direction shows an additional along shore component during weak monsoon period. The Convective Boundary Layer (CBL) height shows increase during weak monsoon phase over both stations due to less cloudiness and subsequent insolation. The CBL height during the southwest monsoon is more over Mangalore and is attributed by the orographic lifting in the windward side of the Western Ghats while the influence of the Ghats is less over Trivandrum.

Key words : *Convective boundary layer, Conserved variable analysis, Low level Jet stream, thermodynamic structure*

1. Introduction

The southwest monsoon rainfall is not uniform throughout the season (June-September) and it is characterised by the spells of rainfall over a large area (referred to as active phase of monsoon) during which extensive, organized convective clouds form, separated by periods of little or no rainfall (weak or break phase of monsoon). These active and weak episodes are associated with enhanced (decreased) rainfall over central and western India and decreased (enhanced) rainfall over the southeastern peninsula and eastern India (Singh *et al.*[1]; Krishnamurthy and Shukla[2]). The intra seasonal variations of rainfall (active-break cycles) are strongly coupled to the intra seasonal variations of circulation (Hartmann and Michelson[3]; Webster *et al.*[4]; Sperber *et al.*[5]; Goswami and Ajayamohan[6]). Rainfall associated with the cycles is an outcome of several processes in the atmosphere. In the atmosphere the most important one is the condensation of water vapour from the nimbostratus or stratocumulus clouds (i.e. formed as part of the monsoon organized convection). The vertical distribution of heating and temperature change, including the level of maximum heating is observed to be different in different regions (Frank and McBride[7]). Therefore, details pertaining to the response of the atmosphere to convection and ABL characteristics need to be established from observations for each region. Thermodynamic structure of the Atmospheric Boundary Layer (ABL) varies with these episodes of monsoon. Thermodynamic studies for marine atmosphere and east coastal stations were carried out using BOBMEX-99 data set employing conserved variable analysis (Morwal and Seetharamayya[8]). Balasubramanyam and Radhika[9] made similar analysis using the INDOEX-90 cruise data set over the central Arabian Sea. Parasnis and Morwal[10] carried out the Conserved Variable Analysis of convective boundary layer for the southwest monsoon over Deccan Plateau. Kusuma *et al.*[11] reported that the boundary layer height is high during weak monsoon and it is low during active monsoon phase. The west coastal stations show significant variations during monsoon season according to the movement of Low Level Jet stream

(LLJ) and subsequent convective clouds. The objective of the study is to understand the features of the ABL during active and weak phases of monsoon employing Conserved Variable Analysis (CVA) based on equivalent potential temperature and humidity. The vertical variation of the parameters such as humidity, virtual potential temperature and wind are also studied during the different epochs of monsoon. This study helps in diagnosing ABL processes and the thermodynamic structure.

2. Data and methods

The present study is carried out using radiosonde data during the southwest monsoon period. We employed CVA (plot *theta*-e against *q*) to understand the differences in boundary layer height over the two selected stations in the west coast of India namely, Trivandrum and Mangalore (Fig. 1). These stations are located almost perpendicular to the low level flow of the monsoon wind and the radiosonde

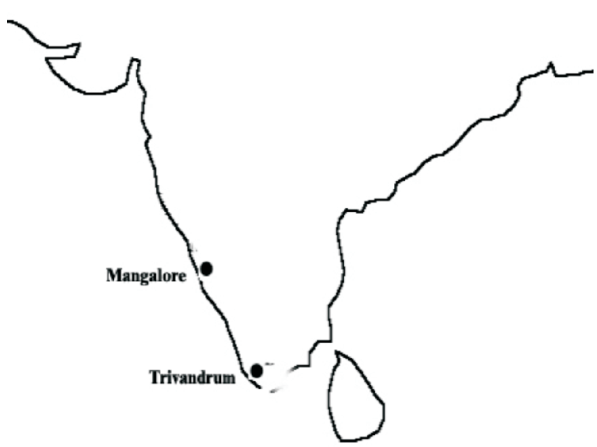

Fig. 1 : Location of Trivandrum and Mangalore situated in the west coast of India

observations are taken at 12:00 UTC. The analysis is carried out considering many active and weak spells during normal monsoon years. The active and weak days are identified using all India daily monsoon rainfall procured from IITM, Pune. In this analysis, active days are considered when the daily rainfall is more than 12 mm and weak phase when the rainfall is less than 8 mm consecutively for at least 3 days. Here, the results are presented for one active monsoon situation during 8th to 13th July, 2001 and for one weak monsoon situation during 18th to 23rd July, 2001. In the convective or mixed boundary layer, the convective clouds can influence radiative process and hence the thermodynamic structure of the atmosphere (Betts and Albrecht,[12]). During a radiative process the magnitudes of *q* will not change, but radiative cooling moves points to lower *theta-e* at constant *q*. The Convective Boundary Layer (CBL) mixing line shows intense mixing of the lower atmospheric constituents within the mixed layer. CVA incorporates all these aspects. The thermodynamic parameters are evaluated as detailed in Babu[13].

3. Results and discussions

The dynamic and thermodynamic structure of the ABL is investigated over the above stations. From the analysis, it is noticed that considerable variations take place from active phase to weak phase of Indian summer monsoon. Fig. 2 gives the vertical distribution of different meteorological parameters such as mixing ratio (g/kg), wind speed in knots, wind direction (degree) and virtual potential temperature (K) during active and weak phases of monsoon. In the figure left panel shows the parameters on a day (11th July, 2001) during active monsoon situation and right panel shows on a day (20th July, 2001) during the weak monsoon situation. Solid line with rectangle represents the station, Trivandrum and the 'x' marked solid line represents the station, Mangalore. Mixing ratio is one of the important parameters deciding the convective activity. This parameter shows high values throughout the layer up to 5 km during active phase in comparison with weak phase. It is also noted that the value is more over Mangalore than that over Trivandrum during both the active and weak phases. It may be due to the high moisture pumping associated with LLJ core from the marine atmosphere to Mangalore station, modulated by the orographic lifting and wind direction perpendicular to the coast.

Vertical variation of the wind shows considerable difference from active to weak. Sam and Vittal Murty[14] showed that the LLJ wind core speed reaches 55 knots during active phase and it becomes 10 knots during weak phase by analysing the upper air data over five stations. However, it is found that the maximum wind core during active situation is around 38 knots over Trivandrum and Mangalore. The core height lowers during active monsoon phase and is around 1.2 km over Trivandrum and that over

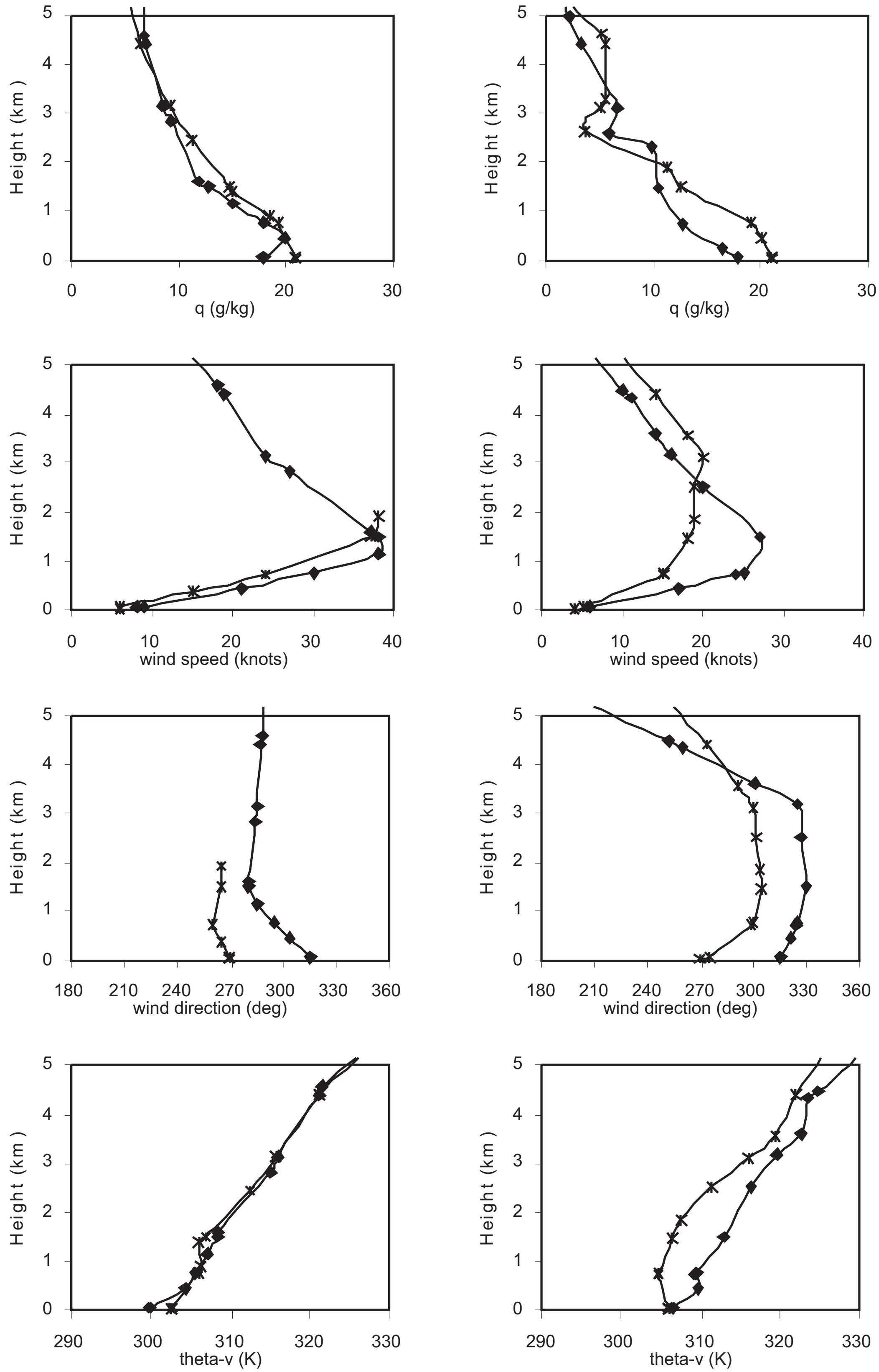

Fig. 2 : Vertical variation of the boundary layer parameters during active : 11th July (first column) and weak : 20th July (second column) phases of southwest monsoon. Line with solid rectangle represents Trivandrum and with 'x' mark represents Mangalore

Mangalore is around 2 km. The relatively high maximum wind core height at Mangalore affects the ABL height to increase due to the effect of wind in the windward side of the Western Ghats. The influence of Western Ghats is relatively less over Trivandrum. During weak monsoon period the core wind strength of LLJ decreases considerably. Even during weak conditions, the wind core speed over Trivandrum is more than 25 knots. From the analysis it is found that during weak condition the wind core speed over Trivandrum is not decreased much. The main difference is in the direction. But over Mangalore, the wind strength decreases to about 20 knots (weak) from 38 knots (active). The core height is also changed from 2 km to higher level (during weak). Another point noticed is sharp variation of speed around 2 km level during active situation, which is not observed during weak phase. Rather a constancy of speed is observed from 1.5 km to 3 km during weak in most of the cases. The wind direction also shows differences during active and weak phases of monsoon. Over Trivandrum the wind is directed northwesterly in the lower levels and westerly above 1.5 km but over Mangalore the wind direction is always westerly in the active monsoon phase. During weak situation, the wind shows an additional along shore component up to 3 km in both the stations due to the forcing by the organised convective cloud band, which formed over the Northern equatorial Indian Ocean as part of next monsoon surge.

Last row of the Figure 2 shows the variation of the virtual potential temperature (theta-v) during active and weak periods of monsoon. Generally theta-v is found high during weak phase of monsoon than active monsoon phase. This increased value of theta-v is may be due to the abundant insolation during the weak monsoon phase since the organised convective clouds are absent.

The convective boundary layer is formed due to the sufficient mixing of lower troposphere due to the thermal activities after the sunrise and subsequent insolation. Fig. 3 and Fig. 4 show the CVA plots depicting theta-e versus *q* for six consecutive days (from 8th July to 13th July) during one of the active monsoon phases for the evening radiosonde observation (05:30 hr IST or 12:00 UTC) for Trivandrum and Mangalore respectively. In the figure, *q*-axis is reversed so that a sounding plotted superficially resembles a more familiar (theta-e-*p*) plot. From the figure, it is found that the CBL height is confined within 1 km except in the last day of the active phase. Table 1 describes the CBL heights during active monsoon situations over Trivandrum and Mangalore. The CBL height values over Trivandrum for the active situations are 302 m, 569 m, 464 m, 569 m and 1180 m for the days 8th, 9th, 10th, 12th and 13th July respectively. The CVA plot for 11th July is peculiar and it is difficult to estimate the CBL height.

TABLE 1

CBL Height during active monsoon phase

Active days	Trivandrum	Mangalore
8 July	302 m	915 m
9 July	569 m	730 m
10 July	464 m	1399 m
11 July	-------	1498 m
12 July	569 m	1539 m
13 July	1180 m	2071 m

In the case of Mangalore, the boundary layer height is more than that of Trivandrum. This may be due to the effect of orographic clouds formed over the windward side of the Western Ghats during active monsoon phase. During active monsoon situation, the surface westerly wind over the station increases due to the influence of strong LLJ associated with active monsoon. The CBL heights over Mangalore are 915 m, 730 m, 1399 m, 1498 m, 1539 m and 2071 m respectively for the six days during the active monsoon. The values obtained are realistic even though the vertical resolution of the radiosonde observations is small.

The CBL heights during weak monsoon situations over the two stations are presented in Table 2. During the case of weak monsoon situations the convective boundary layer height is found to be high in all the cases of Trivandrum and Mangalore. Fig. 5 and Fig. 6 show the conserved variable analysis (*theta-e - q plot*) for the weak monsoon days (18th July-23rd July) in the year 2001 for Trivandrum and Mangalore respectively. Over Trivandrum, the CBL mixing height is higher than that during active monsoon. This increase is attributed to the characteristics of the weak monsoon situation. During weak phase the convective cloud band and LLJ core prevail over the equatorial region. Accordingly, convective cloud band and associated rainfall over Indian continent is less except Himalayan regions. The rest of the place is more or less cloud

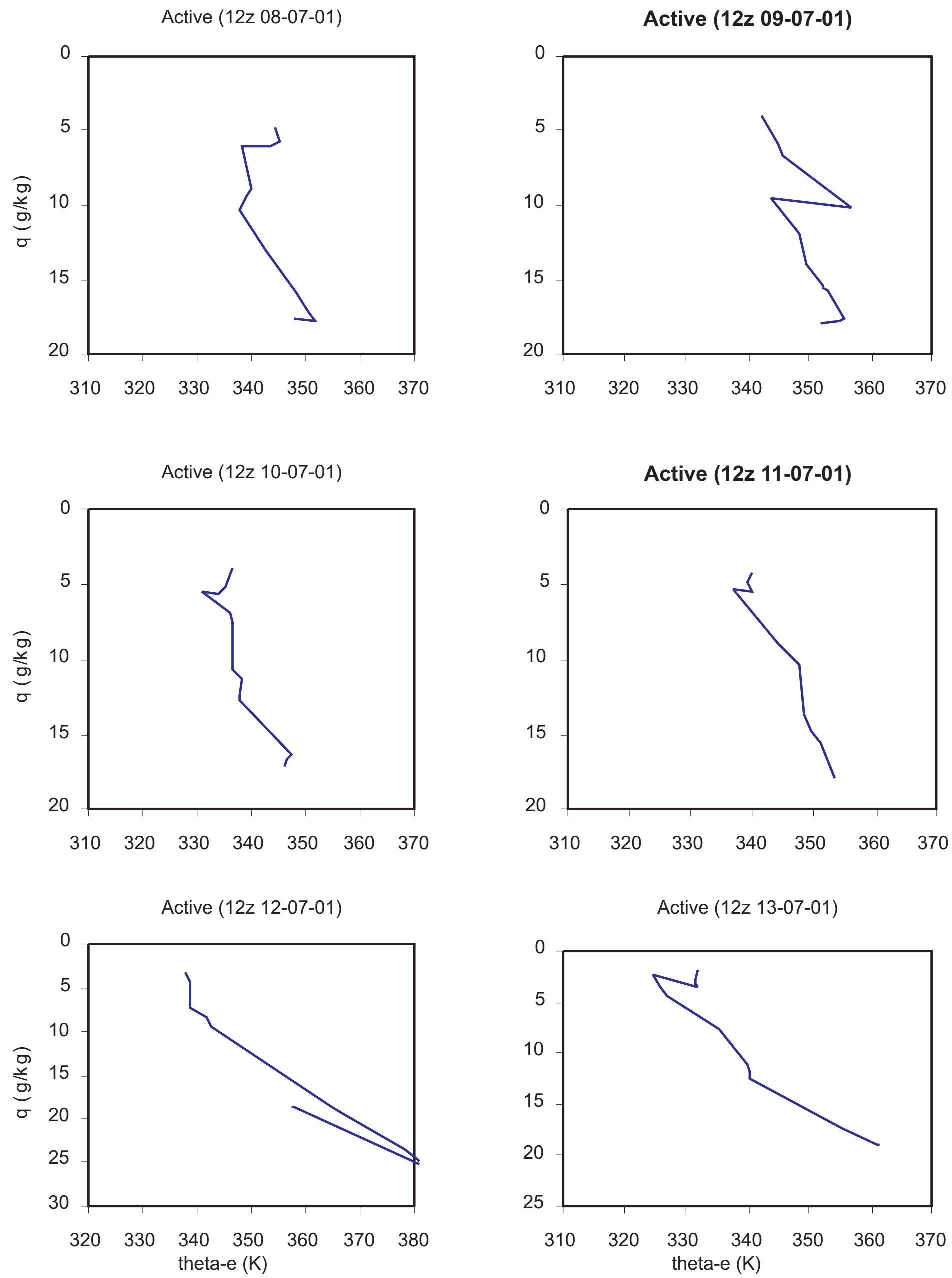

Fig. 3 : Conserved variable analysis for Trivandrum during active phase of monsoon

TABLE 2

CBL height during weak monsoon phase

Weak days	Trivandrum	Mangalore
18 July	1056 m	3129 m
19 July	764 m	763 m
20 July	1473 m	------
21 July	-------	1852 m
22 July	1477 m	2618 m
23 July	400 m	2792

free and transparent to the insolation. Thus the local heating triggers convective activity and hence increases in the mixing height. The mixing height values over Trivandrum during weak situation are 1056 m, 764 m, 1473 m, 1477 m and 400 m for the respective six weak days ie 18^{th}, 19^{th}, 20^{th} 22^{nd} and 23^{rd} respectively. There is no reversal of *q* on the 21^{st} July, so it is difficult to estimate the mixing height based on the CVA. In the case of Mangalore the CBL mixing heights are 3129 m, 763 m, 1852 m,

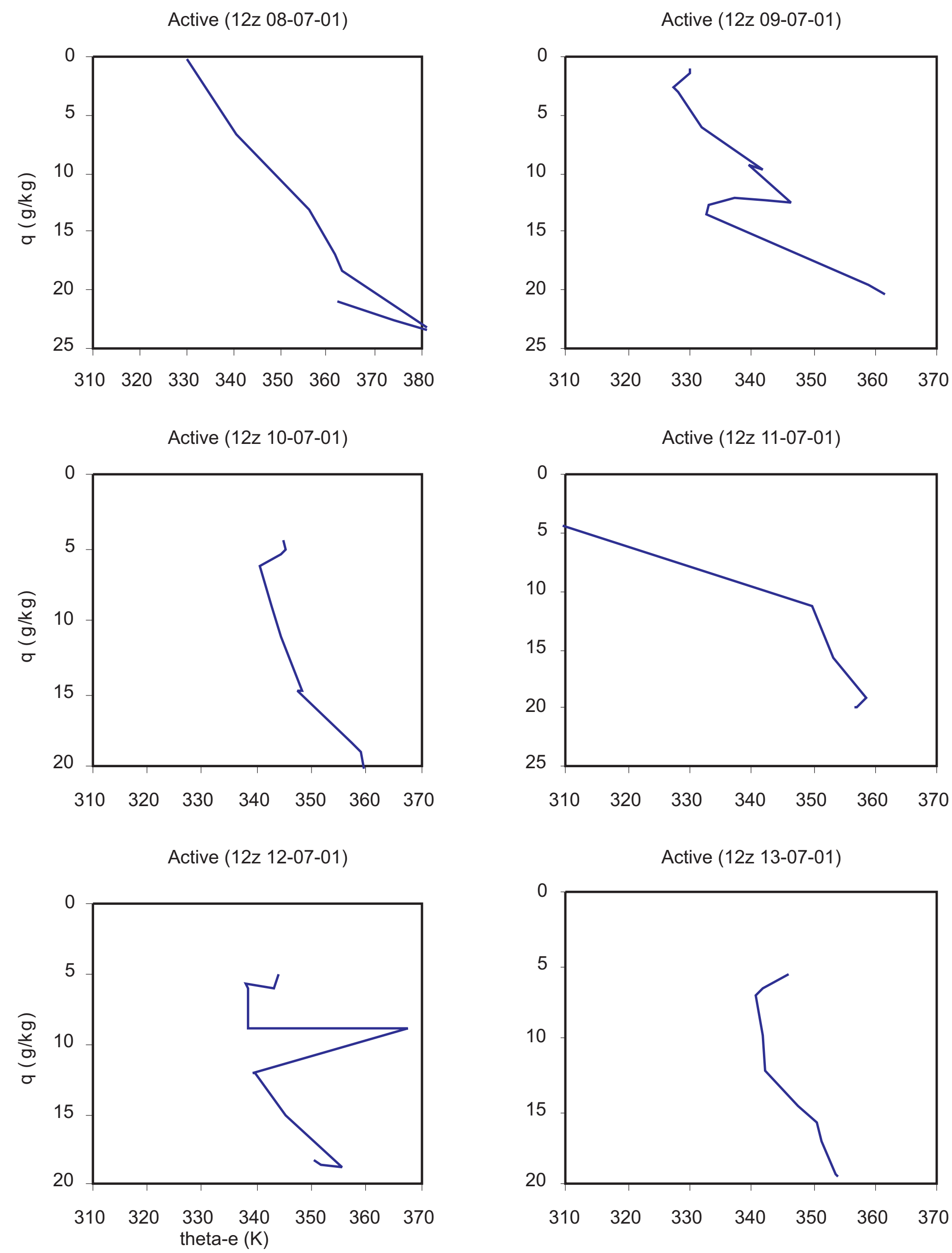

Fig. 4 : Conserved variable analysis for Mangalore during active phase of monsoon

2618 m and 2792 m for the 18th, 19th, 21st, 22nd and 23rd respectively.

4. Conclusions

Vertical distribution of various dynamic and thermodynamic parameters are analysed and discussed. Generally, all the parameters show considerable variations between active and weak monsoon phases. The wind core speed increases and core height decreases during active monsoon situation. The core speed is found to be more than 38 knots in the active monsoon phase around 1.2 km over Trivandrum and around 2 km over Mangalore. During weak monsoon phase the core wind speed decreases and core height elevates. The wind direction shows an additional along shore component during weak monsoon period. From the conserved variable analysis it is found that the CBL height is more during weak phase of monsoon due to less cloudiness. The CBL height values over Mangalore are high compared to that over Trivandrum.

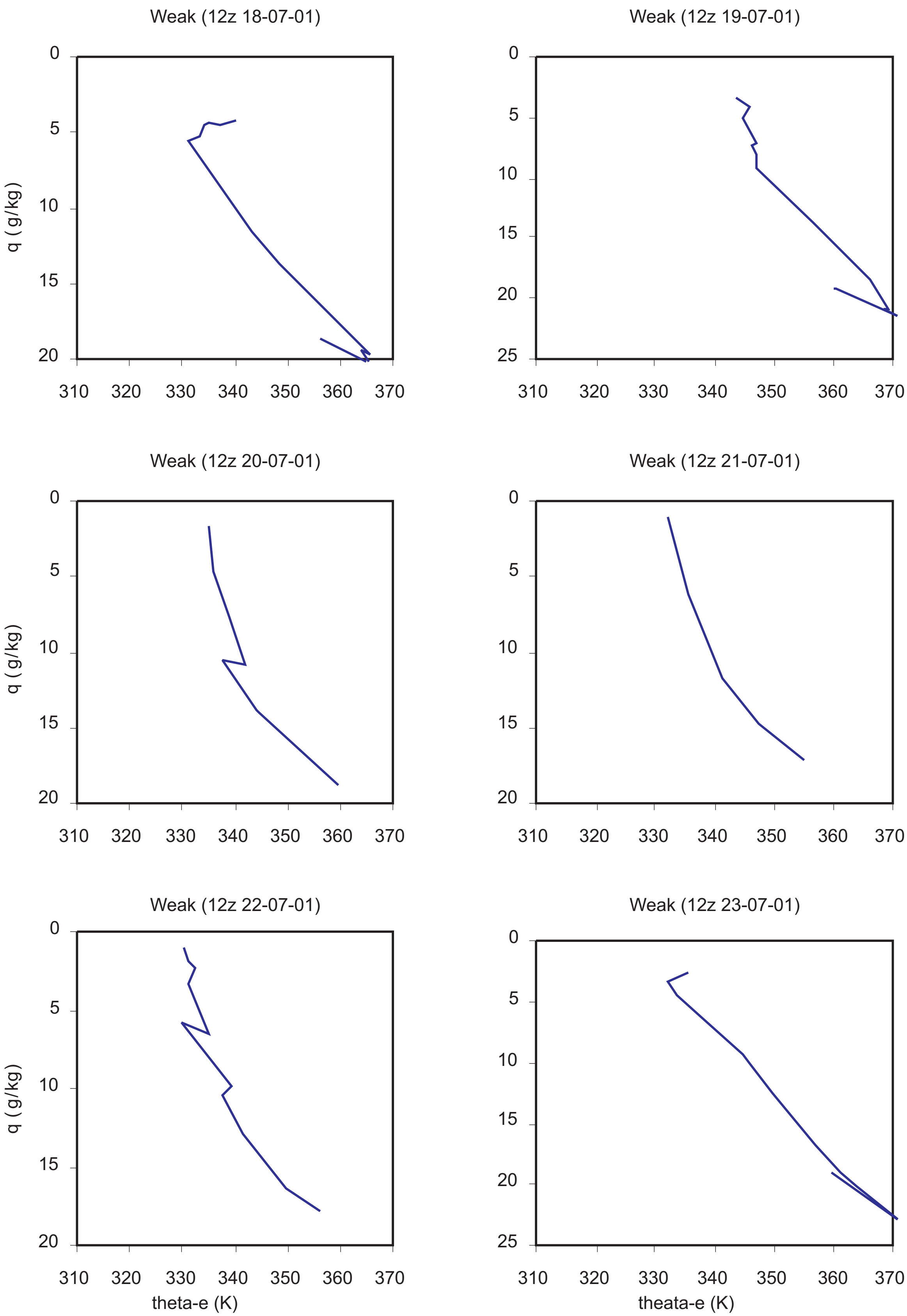

Fig. 5 : Conserved variable analysis for Trivandrum during weak phase of monsoon

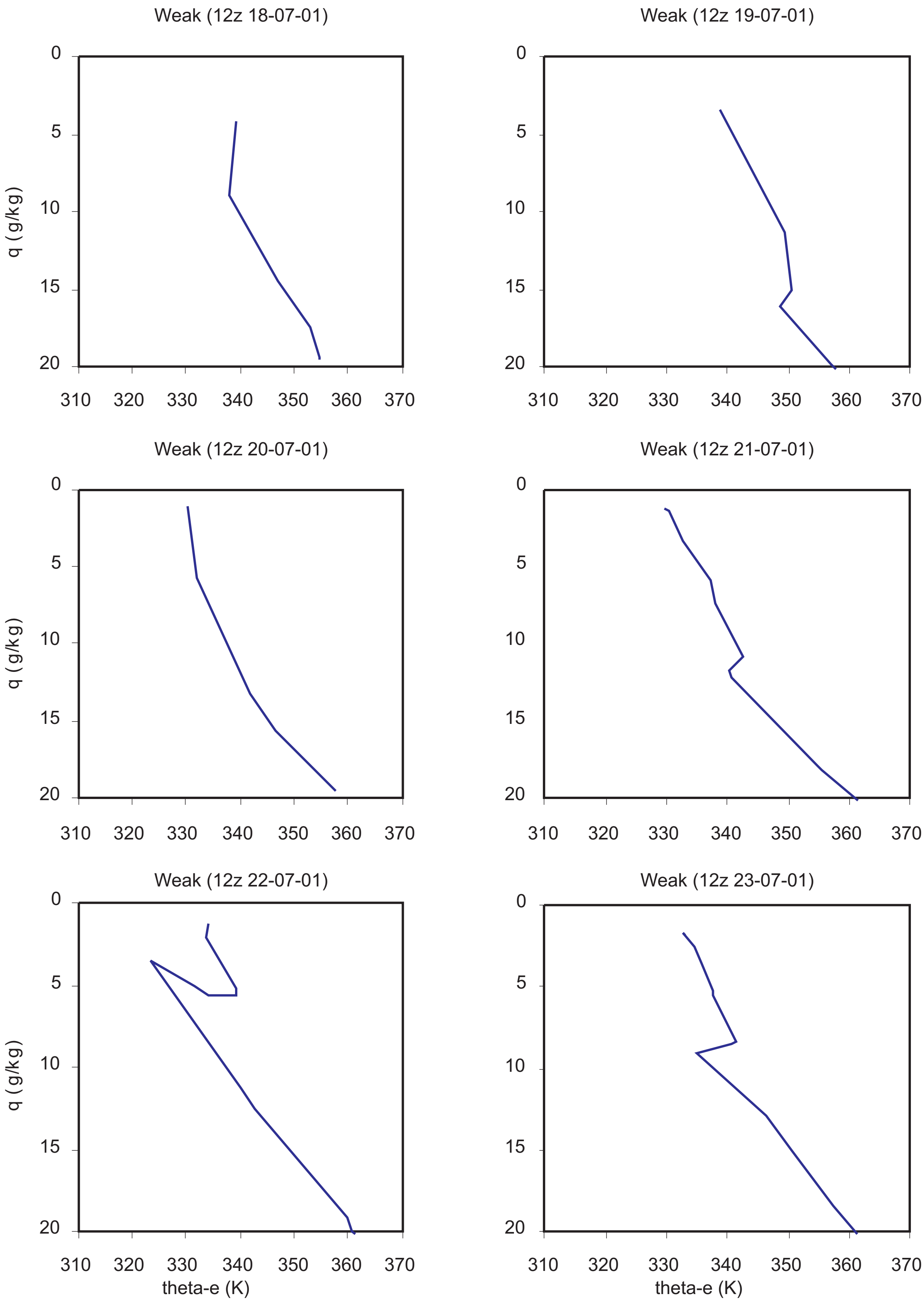

Fig. 6 : Conserved variable analysis for the Mangalore during weak phase of monsoon

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Heavy rainfall / snowfall events over Kashmir valley in the recent period

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ABSTRACT

Heavy rainfall / snowfall over Kashmir region has generally been observed with strong weather systems resulting into avalanches, landslides and floods. During the recent period, Kashmir valley has experienced several disastrous weather events. In this paper heavy rainfall / snowfall events during the period 1990-2005 were studied with their spatial and temporal variation and frequency distribution. Synoptic situations associated with the events have been examined and presented. February and March account for maximum cases of heavy precipitation events during the period under study.

1. Introduction

Kashmir valley is a distinct physical region of the state of Jammu & Kashmir and lies in the northernmost part of India. It is a transverse valley, nestled in northwestern folds of the Himalayas and is surrounded on all sides by high mountain ranges, characterized by snow covered lofty peaks. Kashmir valley is distinctly basin shaped, drained by river Jhelum through the Baramulla-gorge. The valley has a length of about 140 km, a width varying from 53 - 55 km and mean elevation about 1840 m above the sea level. Fig. 1 shows the region of Kashmir valley. The mountainous terrain has a pronounced effect on the climate of Kashmir. Further lying in the extra tropical latitudinal belt, Kashmir enjoys extra tropical mountain climate, tempered with moderate monsoon conditions.

The precipitation over Kashmir valley during winter is mostly in the form of snow which occurs in association with passage of western disturbance over the region. During southwest monsoon season Kashmir gets rain due to penetration of monsoon currents through the trenched valley. Under the influence of strong weather systems, heavy

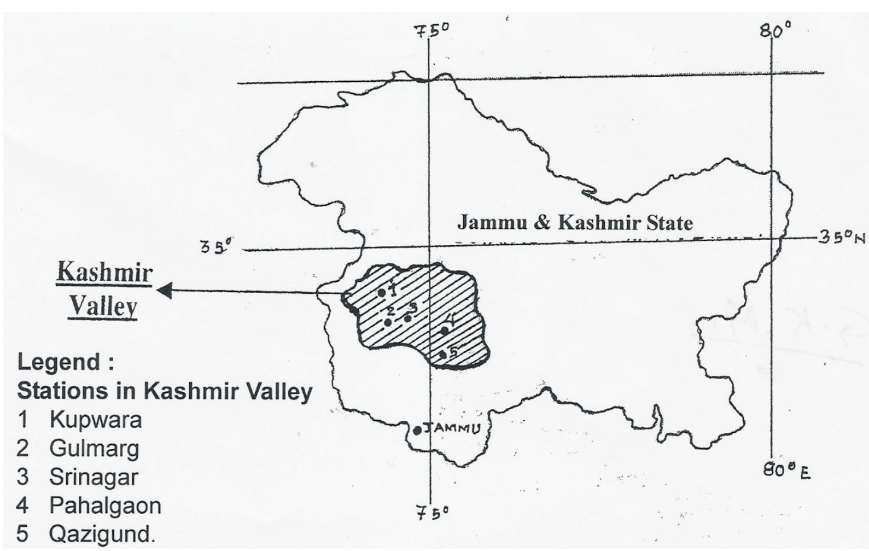

Fig. 1 : Network of IMD observatories in Kashmir Valley

precipitation occurs over Kashmir, some times leading to disaster weather situations causing flood, landslides, avalanches etc. Most recently, in February 2005 the valley witnessed a severe snowfall activity causing enormous loss of life and property.

Several authors have studied Indian rainfall parameter at both subdivisional and state levels. Basu *et al.*[1] has studied monsoon rainfall variability with comparative study in meteorological subdivision of West Bengal. Dubey and Balkrishnan[2] studied heavy and very heavy rainfall over Madhya Pradesh for the period 1977 to 1987. Gore *et al.*[3] studied disastrous weather events of extreme heavy rainfall in West Bengal. The purpose of this paper is to study the spatial and temporal variability of, heavy precipitation events in Kashmir valley during the period 1990 to 2005 and to examine the synoptic situation associated with heavy precipitation events. The study is useful in planning management of disasters arising out of heavy precipitation events associated with western disturbances.

2. Data and methodology

In this study five stations in Kashmir valley, namely, Kupwara (34° 25' N, 74° 18'E), Gulmarg (34° 03' N, 74° 24'E), Srinagar (34° 05' N, 74° 50'E), Pahalgaon (34° 02' N, 75° 20'E), and Qazigund (33° 35' N, 75° 05'E), were selected as shown in Fig. 1. Daily precipitation data of these stations for the period 1990 to 2005 (16 years) have been utilized to compute monthly and annual precipitation averages (normals). Intra-annual and inter-annual variability of precipitation have been studied and presented. Considering the mountainous terrain of the region precipitation amount of 30 mm in 24 hours is assumed a threshold to define a heavy precipitation. Accordingly heavy precipitation events have been identified and their frequency distribution worked out as shown in Table 3. Heavy precipitation amounts exceeding 50 mm in 24 hrs are categorised as intense precipitation and are grouped under (A) 51-100 mm and (B) 101-200

TABLE 1

Mean monthly and mean annual precipitation (mm) and number of precipitation days in Kashmir valley based on period 1990-2005

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
A	120.5	154.0	191.7	129.9	104.9	70.0	91.2	89.6	56.5	36.7	39.1	62.9	1147.6
B	9.3	10.5	12.2	11.0	10.5	8.2	9.2	9.0	6.3	4.0	3.0	5.0	98.0

Note: - A:- Average precipitation in mm   B:- Average number of precipitation days (precipitation 2.5 mm or more)

TABLE 2

Highest recorded snowfall at selected stations in Kashmir during period 1995-2005
Depth of snowfall amount (cm) in each month

	Kupwara		Gulmarg		Srinagar		Pahalgaon		Qazigund	
Month	Amount	Year	Amount	Year	Amount	Year	Amount	Year	Amount	Year
Jan	105.6	2004	290.6	1999	73.2	1999	224.6	2005	268.9	1999
Feb	329.5	2005	661.3	2005	151.6	2005	352.4	2005	319.3	2005
Mar	30.9	2000	416.0	1998	81.7	2002	104.0	1999	81.7	2002
Apr	1.5	2000	242.4	1995	……	……	…….	……	……	……
May	……	…..	229.4	1995	……	…..	42.6	1997	…..	…..
Jun	…….	……	69.2	1995	……..	……	……	……	…….	…..
Jul	…….	……	297.8	1995	…….	……	……..	……	…….	……
Aug	……..	……	…….	……	…….	……	……	…..	…….	…..
Sep	…….	……	28.4	1995	……	……	…….	……	…….	…..
Oct	…..	……	79.7	1995	…….	……	31.8	1996	53.4	1996
Nov	38.7	1997	136.6	1997	39.8	1996	76.2	1997	87.6	1997
Dec	108.4	2003	116.4	1997	41.2	2003	101.5	2003	101.5	2003

TABLE 3

Monthly frequency of heavy precipitation in Kashmir valley during the period 1990 - 2005

Month	No. of events	No. of days	Events E1	With E2	Days D1	with D2
Jan	25	42	20	5	30	12
Feb	35	59	30	5	41	18
Mar	37	66	28	9	44	22
Apr	26	40	23	3	29	11
May	20	29	18	2	25	4
Jun	15	17	14	1	13	4
Jul	19	24	18	1	18	6
Aug	18	23	17	1	18	5
Sep	7	10	7	0	8	2
Oct	7	8	7	0	6	2
Nov	10	17	9	1	14	3
Dec	8	20	8	0	13	7
Annual	227	355	199	28	259	96

Note: Heavy precipitation : Precipitation in 24 Hrs. 30 mm or more

E1: Events with duration 1 or 2 days

E2: Events with duration 3 days or more

D1: Days when 1 or 2 stations reported heavy precipitation

D2: Days when 3 or more stations reported heavy precipitation

mm as represented in Table 4. Weather systems affecting Kashmir valley have been collected from MAUSAM and their monthly frequency presented in Table 6. Selected cases of heavy precipitation events which caused disaster situation in the valley have been discussed.

3. Results and discussion

3.1. Monthly and annual variation of precipitation

Mean monthly and mean annual precipitation and the number of precipitation days (i.e., days with precipitation 2.5 mm and more) during 1990-2005 are presented in Table 1. It was observed that March remained the wettest month with precipitation of 191.7 mm and 12.2 precipitation days. The valley received maximum precipitation in the four months from January to April of the order of 52% of total annual precipitation while the value for the number of precipitation days was 43% of the annual figure. October was the driest month with precipitation amount 36.7 mm and 4.0 precipitation days. During southwest monsoon season (June to September), Kashmir valley received precipitation of 307.8 mm (i.e. 27 % of the annual total) with July receiving a maximum amount of 91.2 mm. Total precipitation days during the season remained about 33 days (i.e. 33% of annual figure). The inter-annual variability of precipitation in Kashmir valley is shown in the Fig. 2. It is found that during this 16 years period, there are 3 occasions when annual precipitation remained excess (departure + 20% or more) during 1992,1994 and 1996, 8 occasions normal (departure +19 % to - 19 %) during 1990, 1991, 1993, 1995, 1997, 1998, 2003 and 2005 and 5 occasions deficient (departure - 20% to - 59 %) during 1999,2000,2001,2002 and 2004. It is also seen that the valley received the highest precipitation 1549.6 mm in the year 1996 and the lowest amount 782.9 mm in the year 2000.

TABLE 4

Number of occurrence of intense precipitation over Kashmir valley during period 1990 - 2005
Intense precipitation amounts (mm) : (A) 51 - 100 (B) 101 - 200

	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec		Annual	
Station	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
KUP	1	-	3	-	6	-	6	-	2	-	-	-	2	-	1	-	-	-	1	-	-	-	2	-	24	-
GLM	11	-	21	3	7	5	5	1	-	-	3	-	3	1	5	-	1	1	-	-	-	-	4	3	61	14
SRN	-	-	4	-	2	-	4	-	-	-	-	-	-	-	1	-	1	-	-	-	-	-	1	1	13	1
PHG	3	-	5	-	4	1	4	-	1	-	-	-	1	-	2	-	2	-	-	-	-	-	2	-	24	1
QZD	7	-	9	2	11	-	3	-	2	-	1	-	5	-	2	3	1	2	1	-	2	-	3	-	47	7
Total	22	0	42	5	39	6	22	1	6	0	4	0	11	1	11	3	5	3	2	0	2	0	12	4	169	23
Monthly Total	22		47		36		23		6		4		12		14		8		2		2		16		192	

Note : KUP- Kupwara, PHG- Pahalgaon, GLM- Gulmarg, QZD- Qazigund, SRN- Srinagar

TABLE 5

Average number of weather systems (Western disturbances and Monsoon systems) in each month over Kashmir valley during the period 1990-2005

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
Average	6.5	6.4	7.1	5.7	3.8	3.3	3.8	4.5	4.0	3.6	4.3	5.3	58.3

TABLE 6

Significant disaster weather events in Kashmir valley and synoptic situation associated

Duration of events	Station	Cumulative precipitation	Disaster weather events & damages	Synoptic situation
Feb 10 -12 , 1991	Gulmarg	233.1	19 persons died and 17 injured due to avalanche. Hundreds of huts destroyed	A western disturbance moved across J & K from 9 to 11
	Qazigund	62.7		
Feb 16 - 19, 2003	Kupwara	114.3	Several persons lost their lives due to heavy snowfall	A western disturbance moved eastnortheastward across J & K from 12 to 19
	Gulmarg	152.1		
	Srinagar	162.9		
	Pahalgam	137.9		
	Qazigund	308.9		
Feb 7 - 9, 2005	Kupwara	96.5	More than 200 people lost their lives due to heavy snowfall & avalanche,about 300 reported missing.	A western disturbance moved northeastward across J & K from 14 to 20
	Gulmarg	170.7		
	Pahalgam	79.0		
	Qazigund	96.2	Many houses destroyed,road transport,power supply disrupted. A record snowfall in the period 1990 - 2005	A western disturbance moved northeastwards across J & K from 14 to 20
	Gulmarg	140.2		
	Srinagar	104.0		
	Pahalgam	121.7		
	Qazigund	180.8		
Mar 17 - 23, 1990	Kupwara	259.9	30 persons died due to flash flood & landslide. Road traffic disrupted	A cyclonic circulation moved eastwards across J & K from 15 to 23
	Gulmarg	364.0		
	Srinagar	203.8		
	Pahalgam	298.7		
	Qazigund	229.4		
July 25 - 28, 1995	Kupwara	124.1	104 persons died, 5000 houses damaged Jammu-Srinagar highway remained closed due to heavy rain and flood	A cyclonic circulation moved eastwards across J & K from 23 to 26. Another cyclonic circulation moved northwestwards from west Uttar Pradesh during 25 to 28
	Gulmarg	271.9		
	Srinagar	101.1		
	Pahalgam	148.0		
	Qazigund	258.0		
Aug 27 - 28 , 1997	Kupwara	123.3	48 persons died and 400 cattle perished, road traffic disrupted due to heavy rain & landslide	A depression lay near Jaipur on 25, near Ganganagar on 27 and moved northwards weakening gradually
	Gulmarg	130.6		
	Srinagar	87.7		
	Pahalgam	120.2		
	Qazigund	282.3		
Dec 25 - 29, 1994	Gulmarg	345.0	Normal life disrupted. Kashmir valley cut off due to snow storm	A western disturbance moved across J & K. A trough in mid/upper tropospheric westerlies located along Long. 69^0 E north Lat. 15^0 N on 28 and moved northeastwards
	Srinagar	81.1		
	Pahalgam	169.9		
	Qazigund	274.0		

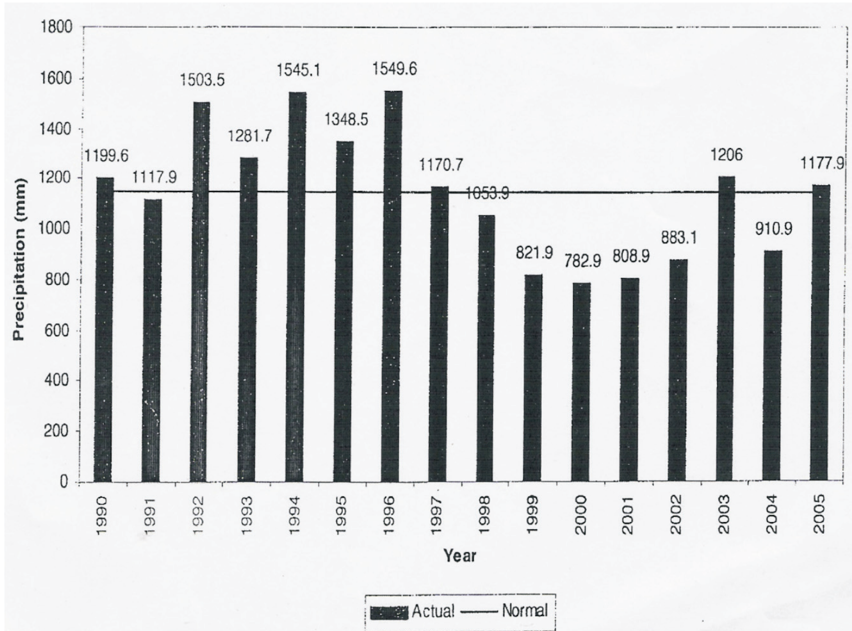

Fig. 2 : Annual precipitation (mm) of Kashmir valley

Heaviest snowfall depth recorded in different months at the selected stations during the period 1995 - 2005 are presented in Table 2. It is clearly seen that all the five stations received heaviest snowfall in February 2005. Gulmarg received maximum snowfall of 661.3 cm in that month. Generally the snowfall over Kashmir starts from November and continues till March; however, higher reaches in the region receive snowfall in other months also. Snow in often mixed with rain but the precipitation in the months January and February is mostly received in the form of snow. Snow starts melting in April and adds substantially to the run-off of the streams flowing in the region.

3.2. Occurrence of heavy precipitation events

Monthly frequency of heavy precipitation events in Kashmir valley are presented in Table 3. It is seen that maximum cases of heavy precipitation events were in the months from January to May recording highest in the month of March (37), followed by February (35). They were minimum in the months September to December. Out of 227 cases, about 72(32%) ocurred in the months February & March. There were 199 cases with 1 or 2 days duration of heavy precipitation and 28 cases with duration 3 days or more. March and February recorded maximum cases of such events, while September, October & December did not record any event with heavy precipitation for successive 3 days or more. It is also found that maximum heavy precipitation days occurred in the months January to April. Out of 355 heavy precipitation days, there were 259 days when 1 or 2 stations received heavy precipitation in 24 hrs and 96 days with 3 stations or more receiving heavy precipitation simultaneously.

Table 4 shows spatial and temporal distribution of intense precipitation cases. It was found the station Gulmarg lying southwest sector of the valley received maximum intense precipitation cases in both the ranges i.e. 61 nos. in the range 51-100 mm and 14 nos. in 101- 200 mm range. This was followed by Qazigund which lies to the southeast sector of the valley recording 47 intense precipitation cases in the range 51-100 mm and 7 nos in range 101- 200 mm. It may be noted that both Gulmarg and Qazigund lie on the northward slope of Pirpanjal mountain and show pronounced influence of the orography. Srinagar which lies in the central part of the valley received least number of intense precipitation cases i.e. total 14 cases. There were total 192 cases of intense precipitation with highest frequency of 169 in 51- 100 mm range during 1990- 2005. The monthly distribution of intense precipitation shows that out of total 192 cases, highest 47 cases of intense precipitation occurred in the month of

February followed by 36 cases in March. In these two months (February and March) period, 83 intense precipitation cases occurred which was 43 % of the annual total. Further, maximum 11 cases of intense precipitation in the range 101-200 mm were also noted in this period showing the noticeable effect of strong western disturbances during these months. List of significant disaster events in recent period is given in Table 6. The severe snowfall was observed in February 2005 was the heaviest snowfall during the period 1990 - 2005 and caused enormous loss of life and property.

3.3. Weather systems affecting Kashmir valley

Monthly frequency of weather systems affecting Kashmir valley are presented in Table 5. On an average, there are about 58 weather systems affecting the valley in a year with highest monthly frequency of 7 systems in March. During the period (January to April) maximum western disturbances affect the region. Mostly they approach from Pakistan and Afghanistan and move generally eastwards across the valley giving maximum precipitation over the region. They are seen as upper air cyclonic circulations in lower levels; some times extending up to mid tropospheric levels. The precipitation that the valley receives during this period is of great significance for fruit, crops and agriculture. The precipitation during southwest monsoon generally occurs in association with the weather systems (Low/ Depressions) originating in Bay of Bengal & moving across North India that affect Kashmir region as upper air cyclonic circulations from south southeasterly direction. In other cases precipitation occurs due to northward shifting of the axis of monsoon trough from its normal position. Incursion of moisture from Arabian Sea, in some cases, contributes significantly to precipitation activity over the region.

4. Conclusion

The study brings out the following salient features :

(i) During the period 1990 - 2005 Kashmir valley receives an average annual precipitation of 1147.6 mm and average 98 precipitation days. Maximum precipitation occurs in the four months period comprising January to April which is about 52 % of annual total. Number of precipitation days in this period is 43 % of the annual figure.

(ii) March remained the wettest month with precipitation of 191.7 mm and 12 precipitation days. October was the driest month with precipitation 36.7 mm and 4 precipitation days.

(iii) The year 1996 recorded the highest annual precipitation of 1549.6 mm and the year 2000 the lowest amount of 782.9 mm.

(iv) Snowfall in Kashmir valley generally starts from November and continues till March; heaviest snowfall during the period 1990 - 2005 was recorded in February 2005. Gulmarg received maximum snowfall of 661.3 cm in that month.

(v) There were about 227 cases of heavy precipitation events and 355 heavy precipitation days in the Kashmir valley during the period 1990-2005. About 32% cases occurred in two months February and March.

(vi) There were 28 cases of successive heavy precipitation of 3 days or more duration and 96 days when 3 or more stations received heavy precipitation simultaneously.

(vii) There were total 192 cases of intense precipitation with highest frequency of 169 in 51-100 mm range during 1990-2005 having highest 47 cases in February. Gulmarg received maximum heavy precipitation of the order of 61 cases in the range 51-100 mm and 14 cases in 101-200 mm.

(viii) Maximum disaster weather events occurred in February as a result of heavy snowfall in Kashmir valley leading to avalanches, landslides etc.

(ix) On an average there are about 58 weather systems affecting Kashmir valley in a year with highest monthly frequency of 7 in March.

Acknowledgements

The author is grateful to DGM, New Delhi and DDGM, RMC Kolkata for their approval of his participation in the TROPMET - 2006. He would like to thank S/ Shri I.K.Koul, S.C.Panda and A.K.Pati for their help in collecting and processing the data. Thanks are due to S/Shri L.A.Dhar and R.N.Dash for typing the manuscript.

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Quantification of frost occurrence over northwest India

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ABSTRACT

Thirty years data (1969-70 to 1998-99) of three stations in northwest India -Ludhiana, Hisar and Pantnagar have been used to arrive at the climatology of frost, duration of frost period bound by the first and the last occurrences of frost in the season and the trend in occurrence of frost over the area during winter season. Highest occurrence of frost days has been found during the month of January followed by December and February. Highest frequency of frost days for the season as a whole as well as for individual months has been observed at Hisar followed by Ludhiana and Pantnagar. The average date of occurrence of frost was found to be 15 December for Hisar and 25 December for Ludhiana and Pantnagar, while the average date of last occurrence of frost was observed as 15 February at Hisar, 04 February at Ludhiana and 28 January at Pantnagar. There is a net decreasing trend during all the months and for the season as a whole indicating that incidence of frost is decreasing over the time.

1. Introduction

Frost is a persistent limitation to the production of many important crops in northwest India during winter season. Tender leaves and flowers of winter crops are damaged due to frost. Frost in temperate climates usually occurs in spring and autumn while cold-weather damage in the sub-tropics is most severe during midwinter. Damage to crops not only causes loss of the production for one year, but also causes loss of the trees or orchard. On calm and clear nights, heat is lost from the surface by radiation to the cold sky. Consequently, the soil and plant surfaces become colder than the atmosphere. The atmosphere near the surface cools and becomes denser so that a stable stratification occurs and a nocturnal inversion is formed. The air near the ground becomes significantly colder than at 15 or 20 m. Mixing in the stable layer increases the convective heat flux and raises the surface temperature (WMO[1]).

Frost is known to occur over northwest India during November to March. Quantification of frost period over the region, average and earliest timings of its initiation in the beginning of the season; and the average and latest timings of its occurrence at the end of growing season provide an important tool to the planners and farmers in adjusting their cropping activities, particularly for frost sensitive crops. (Mavi[2]). Duration of the frost-free period plays a role in the vegetative growth of plants and in the development of successive phases in plant life. WMO[3] presents detailed methodology which helps the plant breeders in developing frost resistant varieties for an area; and to the weather forecasters in keeping a close watch on likely occurrence of frost in the season for issuing advisories on likelihood of frost and selection of appropriate frost prevention methods which include both direct (Mulches Screens, Heaters, Wind Machines, Sanding, Overhead sprinkler irrigation, Brushing, Windbreaks) and indirect methods (Choice of sites, Plant toughening, Resisting cultivars and Use of crop growth regulators and chemicals).

In view of above, present study has been undertaken to quantify the frequency of frost occurrence; and beginning and end of frost season over north-west India. Long term trends in duration, onset and end of frost season have also been attempted. The study could be useful in planning sowing of vegetables and other frost sensitive crops so as to avoid the coincidence of the susceptible stages of the crops with the most likely frost periods. Also the finding could be utilized in breeding suitable varieties and for crop insurance purposes.

2. Data and Methodology

Daily minimum temperatures of the agromet observatories at Ludhiana, Hisar and Pantnagar for

30 years (1969-70 to 1998-99) have been used in the study. Frost generally occurs when the ground temperature falls to near zero degree Celsius. This requires observations on grass minimum temperature which are generally not available at many places. Relationship between grass minimum temperature and the minimum temperature recorded in the screen was studied for Hisar for which daily observations on grass minimum temperatures were available for the entire study period. It was found that, on an average, the grass minimum temperature reaches zero degree Celsius when the minimum temperature in the screen is 3.5 degree Celsius. Therefore, a day having minimum temp of 3.5 degree Celsius or less has been categorized as a frost day. This relationship has been assumed to be applicable to other stations also. The data have been studied for the occurrence of first and last frosts, number of frost days, frost period and their trends. Frost period for a station has been defined as the period between the first and the last occurrence of frost during a particular year.

3. Results and Discussion

3.1 Frequency of frost days

The average numbers of frost days during different months are shown in Table 1. The highest numbers of frost days have been observed during January at all the stations followed by December and February in that order. Very few days in November and March have experienced frost. Therefore, no trend analysis has been done for these two months. It is interesting to note that the frequency of frost is higher at Hisar as compared to Ludhiana and Pantnagar, though Hisar is located south of both these stations. Lighter soil at Hisar and the resultant lower water holding capacity seems to have resulted in this type of pattern in frost occurrence.

Table 1 : Number of Frost Days

Month	Station		
	Hisar	Ludhiana	Pantnagar
November	0.5	0.1	0.1
December	7.5	3.0	1.9
January	11.6	8.1	5.0
February	4.8	2.1	1.8
March	0.4	0.1	0.2
Total	24.8	13.4	10
Trend (days/ decade)	-4.1	-5.2	-1.6

Inter-annual variations in the number of frost days during December, January, February and the season as a whole are given in Figure 1 (a - c). There are large year to year variations in the number of frost days at all the three stations. However, there is a net decreasing trend during all the months and for the season as a whole indicating that incidence of frost is decreasing over the time, which is in synchronous with the findings that minimum temperatures are increasing in North-West India during the last century (NATCOM[4]).

3.2 Beginning and end of the frost season

The occurrence of first and last frost in the season and the frost durations at different stations are given in Table 2. On an average, the occurrence of frost starts in the 2nd fortnight of December over the region. This, however, has been observed to commence as early as 22 November at Hisar, 28th November at Ludhiana and 27th November at Pantnagar. The incidence of frost has been found to cease by January end-February beginning at Pantnagar and Ludhiana and by middle of February over Hisar. However, it has been observed to occur

Table 2 : Commencement, cessation and duration of frost period

	Date of first Frost		Date of last Frost		Frost period (days)	
Station	Earliest Date	Mean Date	Latest Date	Mean Date	Longest	Average
Hissar	22 Nov	15 Dec	09 Mar	17 Feb	95	62
Ludhiana	28 Nov	25 Dec	01 Mar	04 Feb	93	41
Pantnagar	27 Nov	25 Dec	27 Feb	28 Jan	83	40

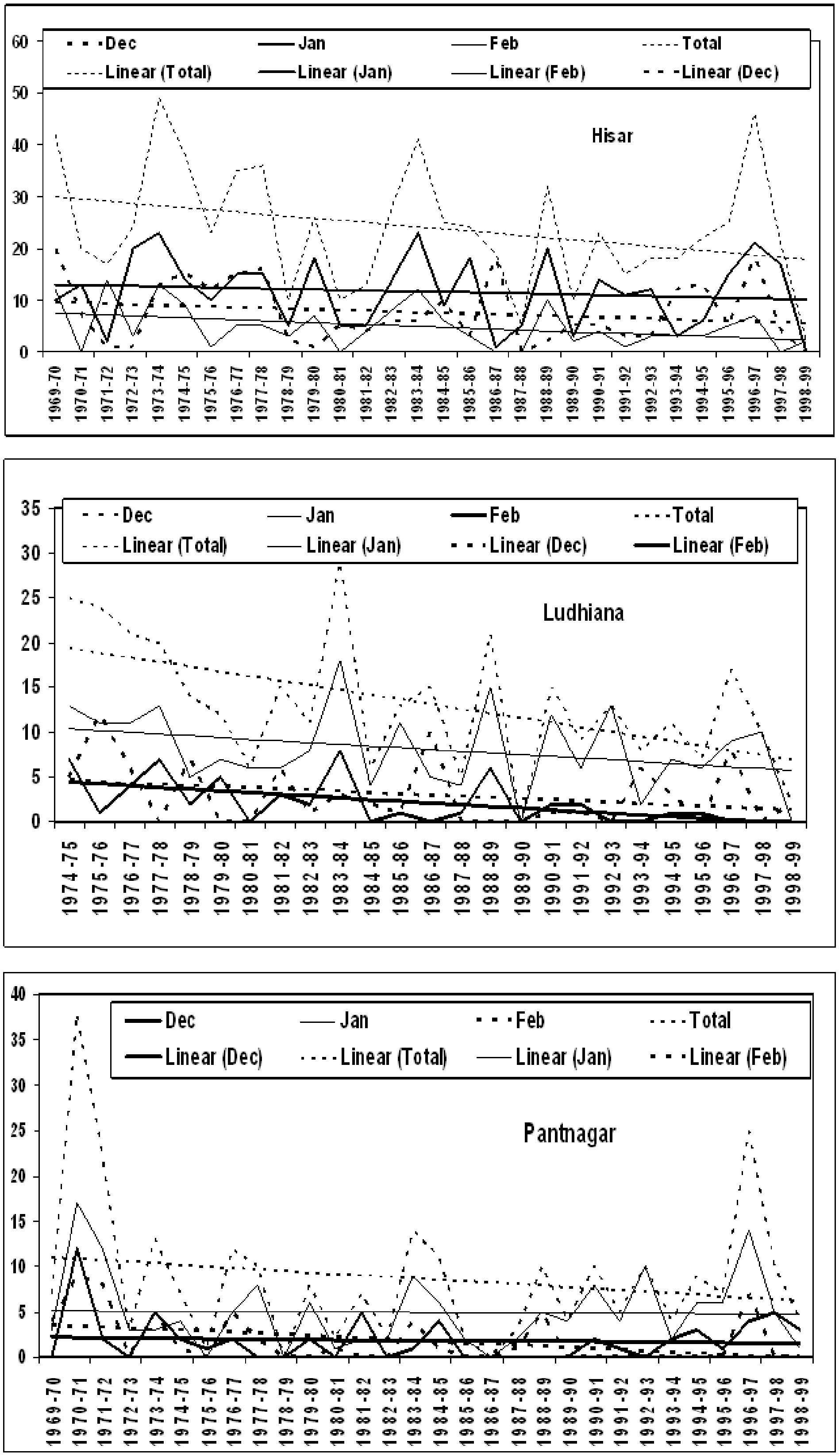

Fig. 1. : Number of Frost days during different Months

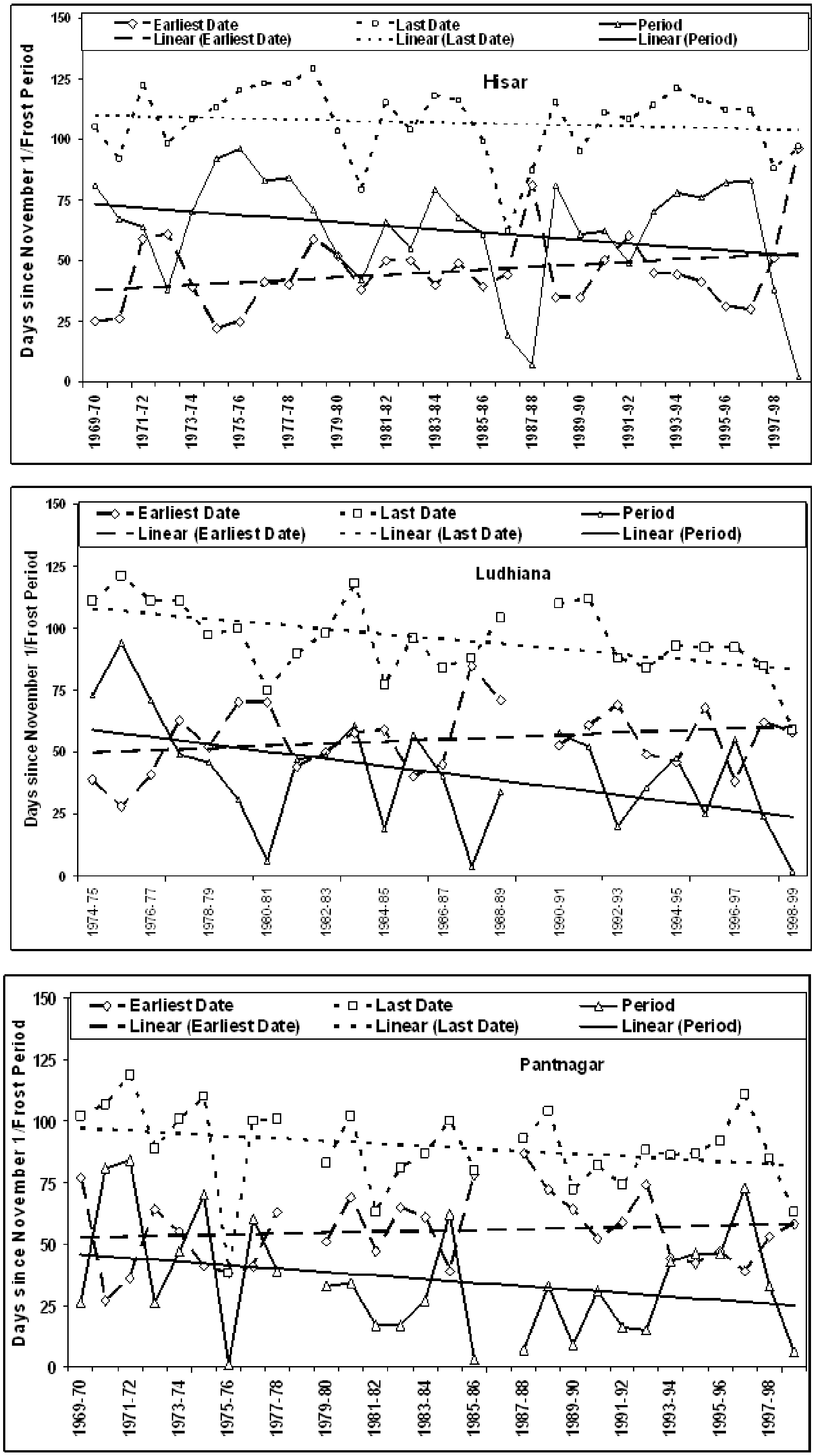

Fig. 2. : Commencement and Cessation of Frost and Frost Period

upto as late as 27 February at Pantnagar, 1 March at Ludhiana and 9 March at Hisar. The occurrence of frost is found to commence much earlier and the cessation of frost much later in the season at Hisar compared to all other stations.

Interannual variation in the occurrence of the first and the last frost in the season, and the frost period are shown in Figure 2 (a-c). The numbers of days since November 1 have been counted for every year to indicate the occurrence of first and the last frost in the season. The figure shows that at all the three stations there is a positive trend in the number of days (since November 1) for the first frost to occur, indicating that there is a tendency for the first frost to occur late in the season during the study period. A negative trend has been observed in the incidence of the last frost in the season, indicating that the frost season is tending to end earlier. A combined effect of the late onset and early end of the frost season results in the decreasing duration of frost period at all the stations.

Table 3 : Trend (days per decade) in the occurrence of the first and last frosts in the season; and the duration of frost period

Station	Date of first Frost	Date of last Frost	Frost period (days)
Hissar	5	-2	-7
Ludhiana	4	-10	-14
Pantnagar	2	-5	-7

This information on the long term trends in commencement, cessation and duration of the frost season (Table 3) could be gainfully utilized by the farmers and the plant breeders in adjusting the sowing dates and for breeding new varieties suited to the shorter frost season.

4. Conclusions

i. Highest occurrence of frost days has been found during the month of January followed by December and February. Incidence of frost has been found practically negligible during November and March.

ii. Highest frequency of frost days for the season as a whole as well as for individual months has been observed at Hisar followed by Ludhiana, and Pantnagar. The average date of occurrence of frost was found to be 15 December for Hisar, 25 December for Ludhiana and Pantnagar

iii. The average date of last occurrence of frost was found to be 15 February at Hisar, 04 February at Ludhiana, 28 January at Pantnagar and 26 January at Delhi and Jaipur.

iv. Long term trend indicates late initiation and early cessation of frost during the season.

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