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Impact of low level jet on heavy rainfall events over Mumbai

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सार – वर्ष 1966 और 2005 के मध्य 21 चुने हुए वर्षों (सामान्य/सामान्य से कम वर्षा) के अखिल भारतीय मानसून वर्षों के दौरान सांताक्रूज (कोलाबा) में हुई भारी (65 मि. मी. से कम अथवा इसके बराबर) से बहुत भारी वर्षा (125 मि. मी. से कम अथवा इसके बराबर) के 186 (168) मामलों का अध्ययन करने से यह पता चला है कि (*i*) जब मीनीकॉय/अमीनीदीव के द्वीपों अथवा तिरूवनंतपुरम से मुम्बई तक प्रायद्वीपीय भारत के पष्चिमी तट के साथ साथ किसी दूसरे क्षेत्र में 850 हैक्टापास्कल पर निम्न स्तर की पष्चिमी हवाएं 30 नॉटस से कम अथवा इसके बराबर चलती हैं और (*ii*) पवन–तापमान– आर्द्रता (डब्ल्यू. टी. एच.) सूचकांक चरम (क्रिटीकल) स्तर पहुँच जाता है तो मुम्बई और उपनगरीय क्षेत्रों में बहुत भारी से अत्याधिक भारी (250 मि. मी. से कम अथवा इसके बराबर) वर्षा होती है। उपर्युक्त निदर्ष के आधार पर यहां तक कि 26 जुलाई को हुई असाधारण वर्षा (944मि. मी.) और 09 सितंबर 2005 को हुई बहुत भारी वर्षा (223 मि. मी.). के सवंहन 24 से 30 घंटे पूर्व मुम्बई के आस पास अनियमित कपासी मेघों की सूचना देते हुए महत्वपूर्ण मौसम चार्टों के माध्यम से सभी प्रकार की घरेलू उड़ानों के लिए पूर्वानुमान लगाया गया है।

ABSTRACT. Study of 186 (168) cases of heavy (≥65 mm) to very heavy rainfall (≥125 mm) occurred at Santacruz (Colaba) during 21 selected years (normal/deficient All India monsoon years) between 1966 and 2005 suggests that (*i*) when the low level westerly at 850 hPa is reported≥ 30 knots by Minicoy/Aminidivi islands or any other station along the west coast of peninsular India from Thiruvananthpuram to Mumbai and (*ii*) Wind-Temperature-Humidity (WTH) index reaches critical value, very heavy to extremely heavy≥ 250 mm) rain occurs over Mumbai and suburbs. Based on above model even unprecedented rainfall of 26 July (944 mm) and very heavy rainfall of 09 September 2005 (223 mm) have been forecast for all domestic flights in the significant weather charts by indicating occasional cb around Mumbai (VABB) 24-30 hours early.

Key words – 850 hPa winds, Dew point depression, Westerly component/Veering/Backing, Freezing level.

1. Introduction

Shyamala *et al.*, (2001) had observed that exceptionally heavy rainfall amounts were recorded on 13th July, 2000 in North Konkan, Gujarat region and Kutch. The following stations such as Basai (Thane) reported 49 cm, Thane Belapur 45 cm, Bhiwandi (Thane) 41 cm and Dharampur (South Gujarat) 39 cm and Santacruz 35. Santacruz recorded 31cm in 1200 UTC observation with a maximum intensity of 5cm/hour during 0830-0930 UTC. Colaba recorded 22 cm during the same period. On 14th July Sanand (North Gujarat) recorded 48 cm, Ahmedabad 33cm, New Kandla (Kutch) 9 cm and Bhuj 8 cm. They further stated that synoptic situations which have been observed in earlier studies such as formation of monsoon depressions, monsoon lows, offshore troughs, low level circulations (LLC), Middle Level Circulations (MTC) and steep pressure gradient along the west coast did not always result in very heavy rains over north Konkan and Gujarat. Although the present study is confined to heavy (HY) to very heavy (VHY) rainfall forecast at Mumbai (Santacruz and Colaba) but findings will clearly indicate the situations under which heavy to very heavy rainfall may be forecast in north Konkan and Gujarat as well.

2. Data

Upper air (850 hPa) wind data (0000 and 1200 UTC) along the west coast of peninsular India for Minicoy (MNC)/Aminidivi (AMD) islands, Thiruvananthpuram (TRV), Mangalore (MNG), Goa and Mumbai (MUM) for 21 years period off deficient/normal rainfall for All India rainfall have been collected. This data includes 13 normal (1971, 1975, 1976, 1977, 1980, 1988, 1997-2001, 2003 and 2005) and 8 deficient (1966, 1972, 1974, 1979, 1986, 1987,

2002 and 2004) monsoon years. Upper air winds and 0300 UTC rainfall data have been collected/received from the records of Meteorological office, Mumbai, Regional Meteorological Centre, Colaba, Mumbai and Additional Director General of Meteorology (Research) Pune.

HY to VHY rainfall cases occurred at Mumbai (Santacruz-182 , Colaba-168) during these years have been examined with reference to 850 hPa wind data.

3. Previous studies

Srinivasan *et al*., (1972) observed that in the lower troposphere westerlies along Konkan and coastal Karnataka become very strong particularly when there is a strengthening of Arabian sea current, which is usually associated with the formation and the movement of a depression or a low from the Bay of Bengal across the central part of the country or even when the monsoon trough is well marked over the country. It has been also observed by them that these strong winds over the peninsula have a core height of about 1.5 km above mean sea level with core speeds of the order of 40-60 knots.

Grossman and Durran (1984) had found the blocking effect of the western Ghats to be adequate for initiating convection on the windward side and could lead to deep convection if the 850-500 hPa layer was sufficiently moist and if the basic monsoon current was sufficiently strong.

Asnani (1993) has also stated that when synoptic scale situation (like formation of a depression over the head Bay of Bengal or position of ITCZ over central India, south of its normal position) is favorable for large scale lifting up air over the Arabian sea, then the low level monsoon current approaching the western Ghats becomes strong and also 850-500 hPa layer becomes moist (not far away from the western Ghats). Shyamala and Shinde (1999) had observed that cyclonic circulation over Saurashtra, South Gujarat region and adjoining north east Arabian sea at 0.9 km and at 850 hPa give rise to wide spread rainfall activity in north Konkan, south Gujarat region and Saurashtra. It is clear that strong cross equatorial flow and abundant moisture supply augment the existing local synoptic situations for occurrence of heavy rainfall over different parts of the country. Kumar (2001) had observed that heavy rainfall over Mumbai occurs only when the cross equatorial flow is strong. Under these conditions Minicoy islands/South peninsular India report at least 30-50 knots winds at different height from 0.6 km to 700 hPa level with core of Low Level Jet (LLJ) around 850 hPa.

4. Methodology

Srinivasan *et al*., (1972) had observed that a weak monsoon is characterized by a sharp decrease of humidity with height (particularly between 850 and 650 hPa), while on days of strong monsoon the wet bulb curve particularly follows saturated adiabat. Below 850 hPa, there is a particularly no change in the dew point curve whatever may be the monsoon activity. Rao (1976) had observed that DPD is generally 4° C or less during active monsoon with the average Dew Point Depression (DPD) at Mumbai during weak monsoon as high as 10° C at 650 hPa. Dutta and De (1999) observed that in most of the cases strength of easterly at 200 hPa (over Mumbai) is much more on the day of light rainfall and also in the most of the cases the depth of layers of westerly wind is less on the day of light rainfall. Rao (1976) had also observed that the normal dry bulb temperature at Mumbai at 500 hPa (18500 feet = flight level FL 185) is about -3° C for July. It may be inferred that during July freezing level may be found at 170 FL or 5100 GPM over Mumbai during normal monsoon conditions, which may go up as moisture accumulates preceding the HY to VHY rainfall conditions. It has been observed that DPD, different wind patterns and height of freezing level play important role in occurrence of HY to VHY rainfall over Mumbai. Kumar (2001) has prepared an index for use in objective forecast for occurrence of HY rainfall over Mumbai by considering 33 cases of HY to VHY rainfall, which occurred over Mumbai (Santacruz) during 1997-2000. DPD, wind patterns (combined) and different freezing level ranges (combined) have been given individual weightage . Weightage for each sub division of the three parameters has been assigned on the basis of occurrence of heavy rainfall cases under a particular category out of total number of HY rainfall occasions :

Criteria	*Heavy rainfall cases*	*Total heavy rainfall cases*	*Weightage*
DPD ≤5º C from 010 FL to 400 hPa and above	24	33	0.7
DPD ≤5º C from 010 FL to 500 hPa	9	33	0.3
Southwesterly to westerly (190º to 290º) from at least 030 FL to 150 FL and above	13	24*	0.5
Veering from at least 030 FL to 150 FL and above	8	24*	0.3
Backing from at least 030 to 150 FL	3	24*	0.1
Freezing level ranges : (GPM)			
4700 – 5100	4	33	0.1
5100 – 5900	23	33	0.7
5900 – 6300	5	33	0.2
> 6300	1	33	0.0

*Upper air winds were available for only 24 cases.

Arithmetic mean has been used for finding an index for each subdivision of the three parameters. Combining the weightage for each of three parameters, an index is equal to minimum critical value of 1.4 has been found necessary for occurrence of heavy rainfall over Mumbai. Sometimes it may happen that critical value of 1.4 is reached by considering only DPD (0.7) and freezing level (0.7) which is enough for forecasting HY rainfall.

Occurrence of HY rainfall over Santacruz or Colaba has been found continuously for four days on a few occasions during any summer monsoon season. However Santacruz recorded HY to VHY rainfall continuously for five days from 1 July to 5 July 2006 which has never been found in 21 years study period :

July 2006 (at 0300 UTC)	2	3	4	5	6	7
Rainfall amount in mm	66.2	164.5	152.0	231.0	120.0	7.1

The duty of the forecaster is not only to forecast the commencement of HY rainfall but also its cessation. Upper air observation of VABB of 5 July 2006 (1200 UTC) has been considered to verify the adopted model.

Criteria	*Weightage*
DPD $\leq 5^{\circ}$ C observed from 010 FL to 400 hPa	0.7 (H)
Backing from 020 FL to 500 hPa (33030 to 20025 knots)	0.1 (W)
Freezing level 5217 GPM	0.7 (T)
WTH index : 1.5; 850 hPa wind : 260 30 knots	

The following synoptic situations have been observed from 1 to 5 July 2006 :

The low pressure area which formed over the north Bay on 30 June became well marked over there on 1 July. It concentrated into a deep depression at 0300 UTC on 2 near 20.5° N / 89.0° E. After crossing Orissa coast between Paradeep and Chandbali around 1500 UTC on 2 it moved west north westwards and weakened into a depression over Vidarbha and neighbourhood at 0900 UTC on 4. Continuing its west north westwards movement it further weakened into a well marked low pressure area over west Madhya Pradesh and adjoining south east Rajasthan by the afternoon of 5. The upper air circulation over Saurastra & Kutch and neighbourhood persisted between 1.5 and 5.8 km above sea level over north east Arabian sea and adjoining Gujarat state till 1 July. It lay over Gujarat state on 2, Gujarat region and adjoining Madhya Maharastra on 3 and 4 and merged with the circulation associated with the depression on 5. The off shore trough at sea level extended from south Gujarat to Kerala coast through out the week with a steep pressure gradient along the west coast.

Santacruz recorded only 20 mm of rainfall between 1200 UTC of 5 July and 0300 UTC of 06 July out of 231(213) mm Santacruz (Colaba) recorded at 0300 UTC on 6 July. Santacruz (Colaba) recorded 7.1 (0.2) mm rainfall on 7 July. So the adopted model failed in recognizing the cessation of HY rainfall on 6 July. Although the wind pattern has negated VHY or extremely HY rainfall occurrence. It has been observed in three cases of HY rainfall over Mumbai when backing of the wind was present only up to 120/150 FL and veering above it up to 200 hPa. In present case backing of the wind (cold air advection) has been found up to 185 FL (500 hPa) and veering above it just up to 235 FL (400 hPa). Under such a situation only HY rainfall may be forecast for July 6. After taking into consideration failure cases also if the westerly component at 850 hPa is reported $\geq$ 30 knots by Minicoy / Aminidivi islands or any other station along the west coast of peninsular India up to Mumbai only then HY rainfall over Mumbai and suburbs may be forecast with the help of WTH index $\geq$ 1.4.

5. Discussion

5.1. *VHY rainfall occasion during 26 – 27 July 2006*

5.1.1. *Freezing level 25–26 July*

Upper air and significant weather (SIG WX) charts issued by World Area Forecast Centre (WAFC) London are being utilized for briefing purposes to all International Flights in India. However for all domestic flights originating from Mumbai (VABB), New Delhi (VIDP). Kolkatta (VECC) and Chennai (VOMM) locally prepared SIG WX charts are being provided along with upper air WAFC charts. All these charts are updated every 6 hours. Locally prepared SIG WX charts are issued at 0300, 0900, 1500 and 2100 UTC with validity period of 12 hours. Before issuing 0300 UTC SIG WX chart on 25 July 2005, 0000 UTC upper air data of Mumbai has been examined. DPD $\leq 5^{\circ}$ C has been found up to 400 hPa (H : 0.7) and veering (290 35 to 090 45 knots) of the wind from 0.6 km (2000 ft) to 200 hPa altitude (W : 0.3). Freezing level has been reported as 4859 GPM (T : 0.1). So the WTH index comes to 1.1. Rao (1976) had mentioned that only evening ascents available at MNC revealed 7° C per km lapse rate in the first km and more than saturated adiabatic lapse rate by 1° C per km up to 600 hPa during July. He has further mentioned that for TRV high lapse rate up to 1 km was not present in the morning whereas increase in lapse rate in the lowest layer in the afternoon had been witnessed at many stations.

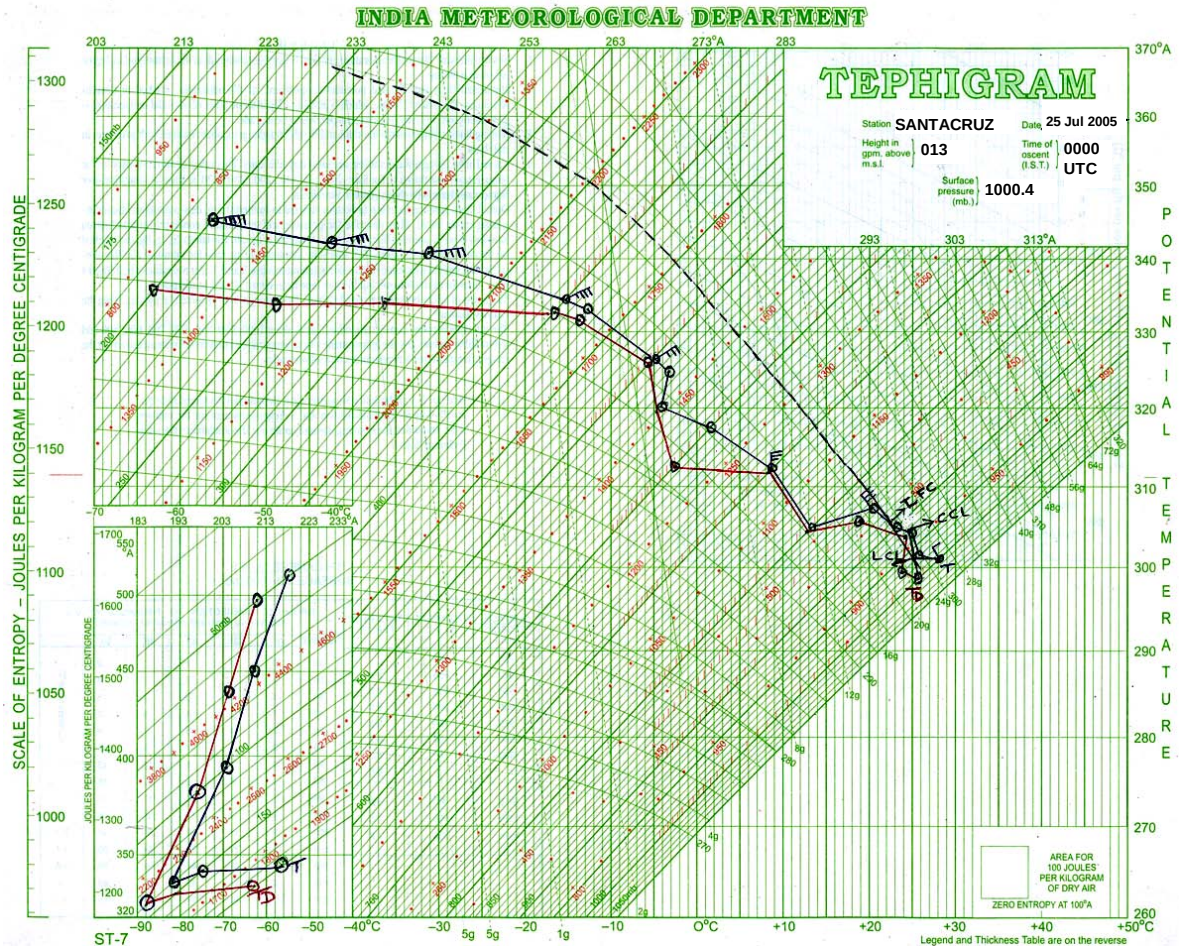

Fig. 1. T-Φ gram of 25 July, 0000 UTC (Santacruz)

Mumbai morning ascent of 25 July showed a lapse rate of 10.5° C in the lowest 1 km, which is more than dry adiabatic lapse rate. This has resulted into low freezing value even when warm air advection was observed from 0.6 km (2000 ft) to 200 hPa (290 35 to 090 45 knots). Taking into account the presence of humidity ($\leq$ 5 ° C) up to 400 hPa, warm air advection up to 200 hPa and Rao (1976) observation of July dry bulb temperature of Mumbai at 500 hPa freezing level appears to be less which has resulted into low WTH index of 1.1. Again on the day of unprecedented heavy rainfall (26 July) the same type of the lapse rate has been found in the lower levels and freezing level was even much lower at 4305 meters (0000 UTC). T–Φ gram of 25 July (0000 UTC) shows level of free convection (LFC) at 915 hPa (approximate) and the parcel remained warmer than environment after crossing LFC (Fig. 1). Severe thunderstorm started around 0900 (to 1200) and moderate thunderstorm continued till 2000 UTC.

5.1.2 *Rainfall distribution during 25-26 July*

Rainfall occurred between 0300 UTC of 26 and 0300 UTC of 27th July at 3 hours interval is as under :

Observation time in UTC	0600	0900	1200	1500	1800	2100	0000	0300
Rainfall (mm)	0.9	18.4	380.8	267.6	101.1	116.2	11.0	48.2

Total 944.2 mm

The maximum intensity was 190.3 mm during 1000 and 1100 UTC. Rainfall rate exceeded 9 cm per hour for 5 hours from 0900 to 1400 UTC. Unprecedented rainfall on this day also occurred in north and north east part of Mumbai which is as under :

Vihar Lake 1049, Ambernath (Thane) 1010, Bhandup 815, Bhivandi 748, Thane 736, Tulsi Lake 601 and Dharavi 493 mm.

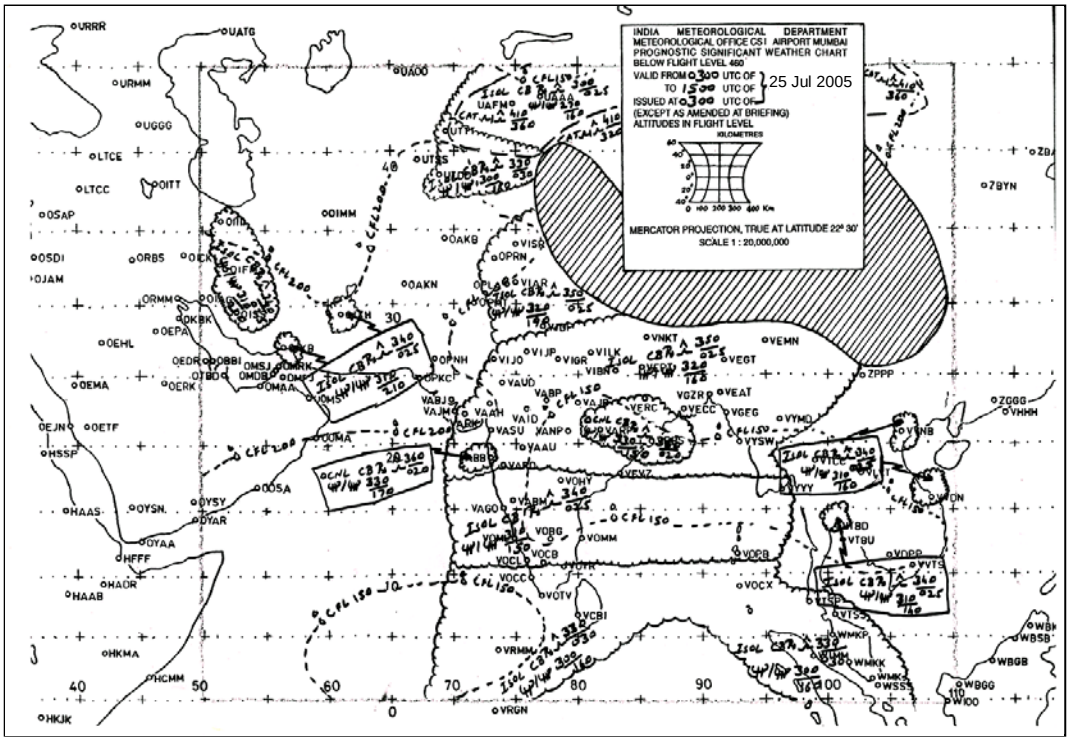

Fig. 2. Significant weather chart, issued at 0300 UTC of 25 July 2005

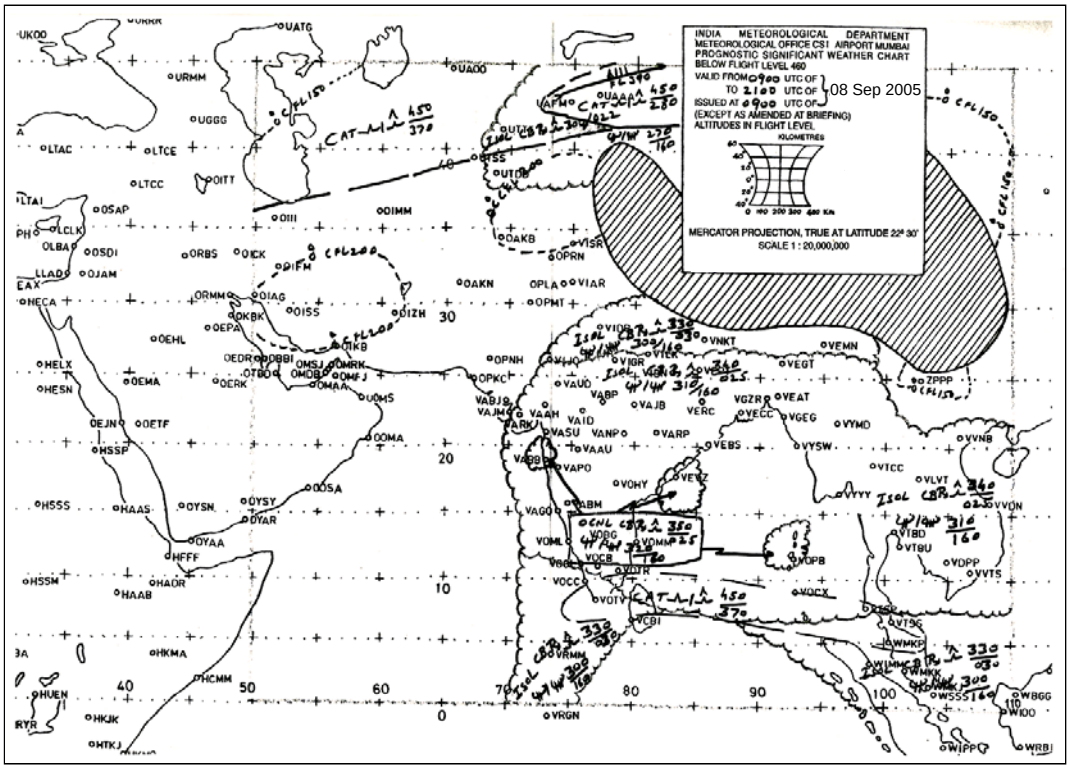

Fig. 3. Significant weather chart, issued at 0900 UTC of 08 September 2005

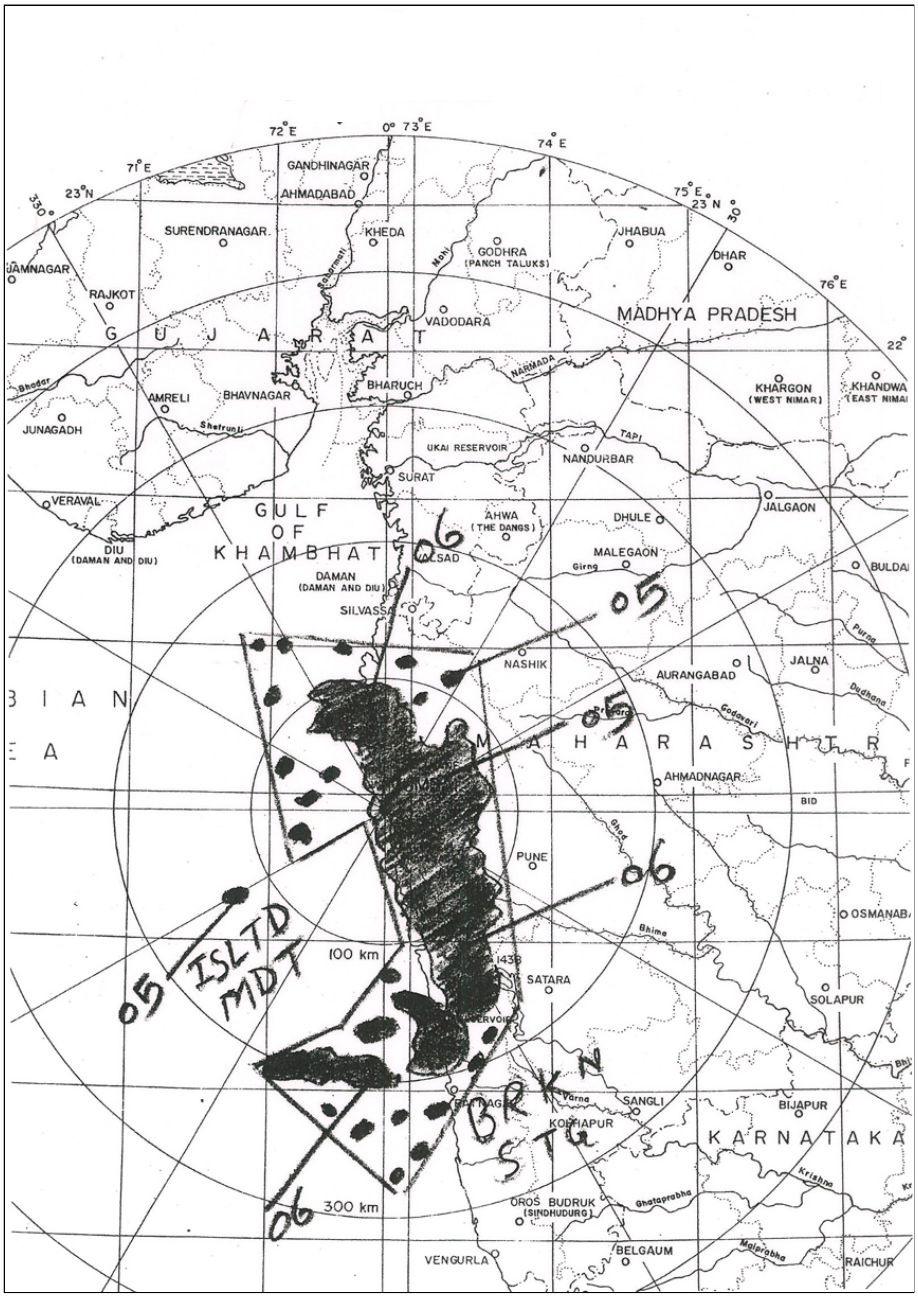

Fig. 4. Cyclone Detection Radar (CDR) Colaba, Mumbai observation at 0600 UTC of 26 July 2005

5.1.3 *850 hPa wind field and prevailing synoptic situation*

It has been observed that 0000 and 1200 UTC upper air data of 24 July for MNC and TRV reported westerly component with 35 knots wind at 850 hPa. Hence after taking into account the critical value and 850 hPa wind along the west coast occasional cb has been marked around VABB in 0300 UTC SIG WX chart of 25 July (Fig. 2). Upper air winds (≥ 30 knots) at 850 hPa reported

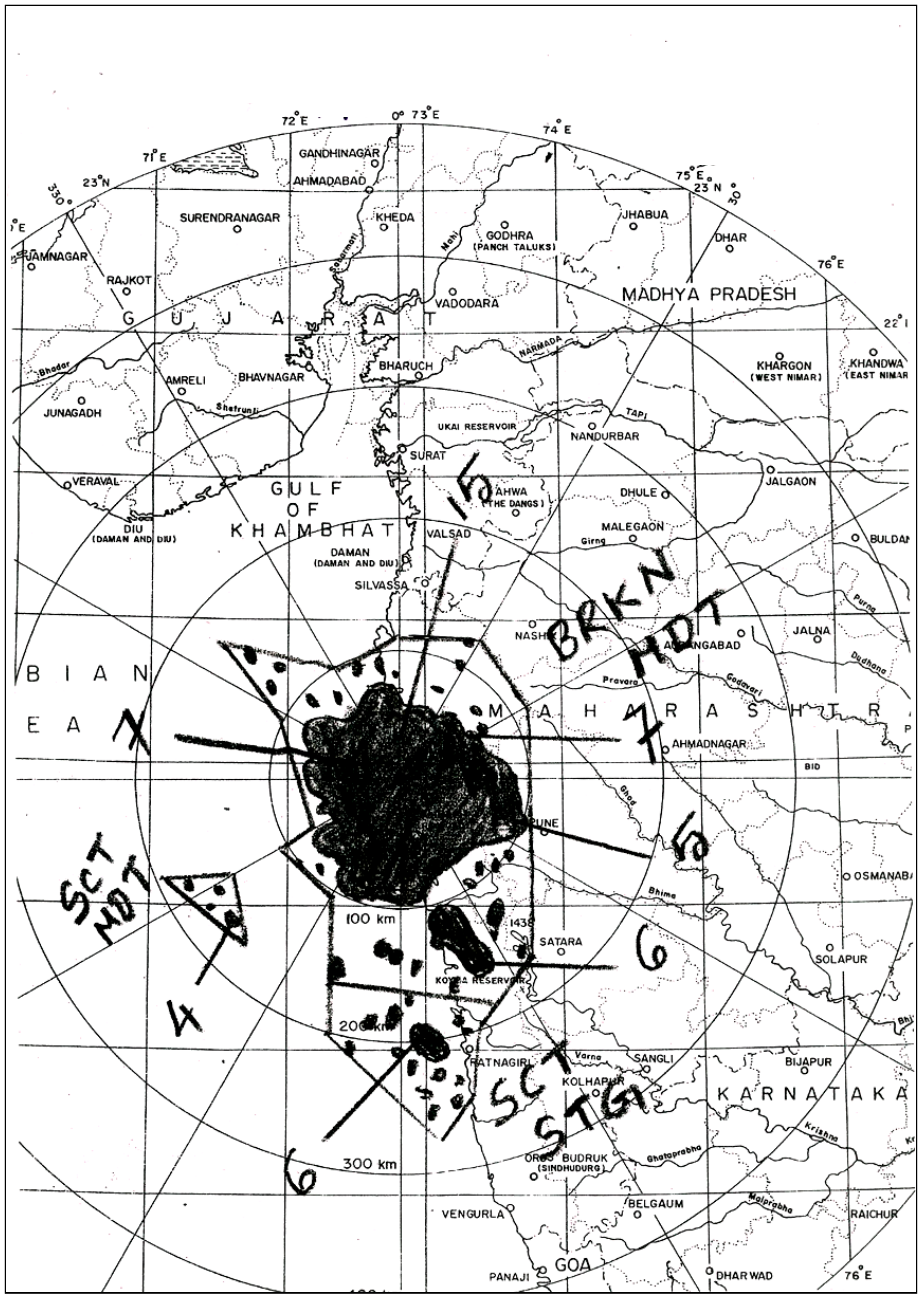

Fig. 5. Cyclone Detection Radar (CDR) Colaba , Mumbai observation at 0900 UTC of 26 July 2005

by stations along the west coast on 25 and 26 July at 0000 UTC are as under:

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Date	*MNC*	*AMD*	*TRV*	*MNG*	*GOA*	*MUM*
25 July 2005	-	29030	29040	29030	-	30030
26 July 2005	28045	-		28040	28045	29035

Upper air winds at 850 hPa reported by different stations on 26th July at 0000 UTC clearly show cyclonic vorticity around Mumbai. Arabian sea monsoon current was strong as 40-45 knots winds were being reported by different stations along the west coast since 25th July. Warm moist air advection over Mumbai continued till

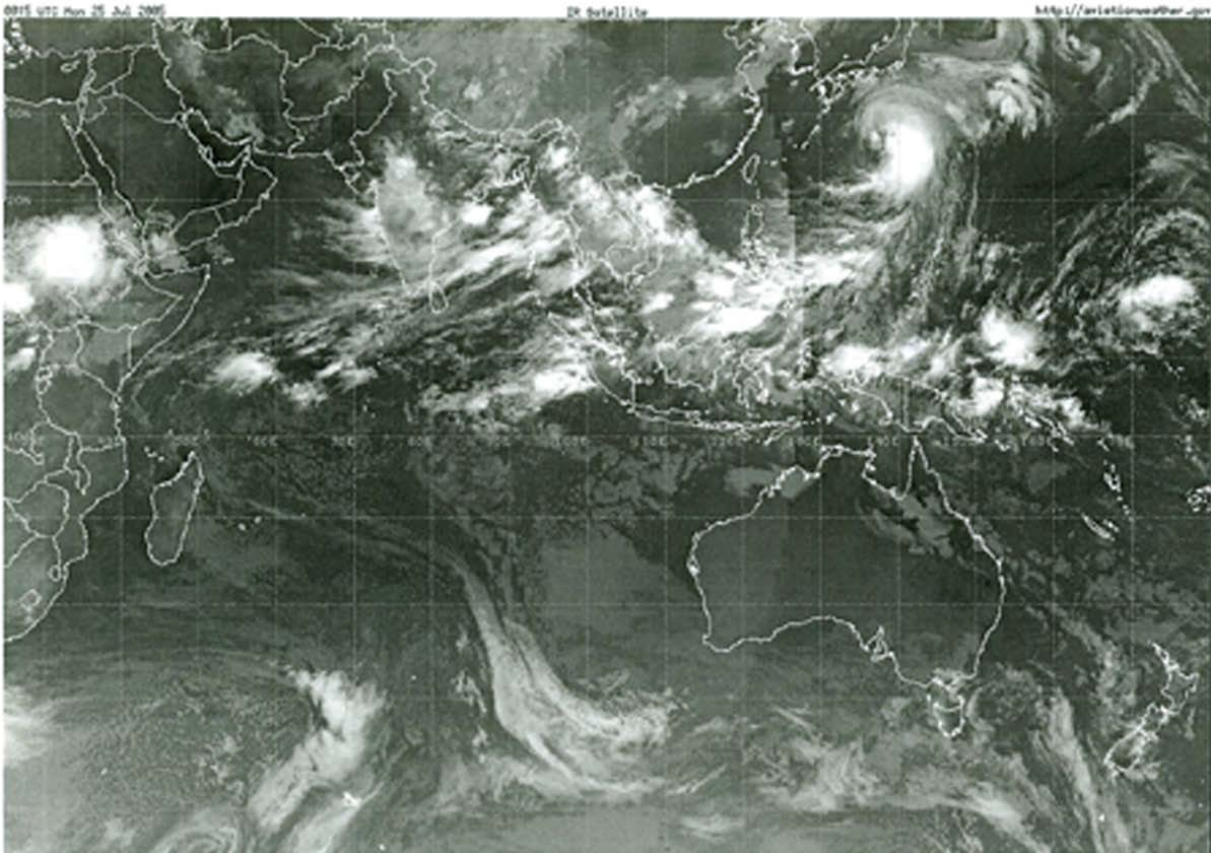

Fig. 6. NOAA Satellite (IR) cloud picture at 0015 UTC, 25 July 2005

26 as veering of the wind up to 200 hPa was also noticed in 0000 UTC upper air observation of 26 (290 35 to 090 35 knots). A low pressure area which formed over North Bay on 23 July became well marked on 24 over North West Bay off West Bengal-Orissa coasts. It persisted there till 25. It moved over northern parts of Orissa and adjoining Jharkhand and Chhatisgarh on 26. It lay as a low pressure area over south east Madhya Pradesh and adjoining Vidarbha and Chhattisgarh on 27. It moved over west Madhya Pradesh and neighbourhood on 28 and became less marked on 29. The off shore trough at sea level extended from Maharastra to Kerala coasts and was quite active in the later half of the week ending on 27 July. Broken strong convective cells of five and six km height have been found by Cyclone Detection Radar (CDR) Colaba, Mumbai in north northwest and south southeast direction at 0600 UTC on 26 July [Fig. 4]. CDR observation taken at 0900 UTC on 26 [Fig. 5] has shown broken intense convection all around between 50-100 km radius from the center with a cell of 15 km height about 40 km north of Santacruz. NOAA satellite cloud picture (IR) taken on 25 July at 0015 UTC [Fig. 6] does indicate accumulation of convective clouds along the west coast north of latitude 12º north (approximately) and subsequent pictures up to 261600 UTC indicated meso scale convective vortex around Mumbai.

5.2. *VHY rain over Mumbai during 9-10 September 2005*

On 08 September 2005 heavy rainfall conditions were again observed. Lapse rate up to 1 km has been found as 9.5º C and 13.9º C in 0000 and 1200 UTC upper air observations respectively. DPD≤5ºC up to 300 hPa (H: 0.7), veering of the wind from 3000 feet to 500 hPa (33005 to 07010 knots; W: 0.3) and freezing level 5235 GPM (T : 0.7) have been found in 1200 UTC upper air observation of 08. The WTH index comes to 1.7. Freezing level was not reached in 0000 UTC observation of 08. TRV had reported 30030 knots wind at 850 hPa in 0000 UTC observation of 08. So occasional cb has been marked around VABB in SIG WX Charts issued at

TABLE 1

Total number of heavy rainfall cases (≥ 65mm) over Santacruz (Colaba) during summer monsoon

Year	June	July	August	September	Total
1966	0 (1)	4 (6)	0 (0)	1 (0)	5 (7)
1971	5 (3)	1 (1)	5 (1)	1 (1)	12 (6)
1972	4 (4)	3 (3)	0 (0)	0 (0)	7 (7)
1974	0 (0)	5 (5)	1 (1)	0 (0)	6 (6)
1975	4 (1)	3 (3)	3 (2)	3 (1)	13 (7)
1976	1 (1)	2 (4)	1 (1)	2 (1)	6 (7)
1977	1 (2)	6 (5)	0 (1)	3 (2)	10 (10)
1979	5 (5)	2 (1)	3 (2)	1 (1)	11 (9)
1980	2 (4)	2 (2)	4 (3)	0 (0)	8 (9)
1986	3 (3)	1 (0)	3 (2)	0 (0)	7 (5)
1987	2 (2)	2 (3)	5 (2)	0 (0)	9 (7)
1988	2 (3)	8 (5)	0 (1)	2 (6)	12 (15)
1997	2 (3)	1 (3)	1 (2)	2 (2)	6 (10)
1998	3 (1)	2 (3)	2 (3)	3 (0)	10 (7)
1999	2 (2)	3 (1)	0 (1)	1 (2)	6 (6)
2000	1 (1)	6 (6)	2 (4)	0 (0)	9 (11)
2001	3 (3)	4 (2)	2 (1)	0 (0)	9 (6)
2002	2 (1)	0 (0)	4 (3)	0 (0)	6 (4)
2003	5 (4)	4 (5)	1 (1)	1 (1)	11 (11)
2004	1 (2)	5 (4)	5 (3)	0 (0)	11 (9)
2005	3 (1)	3 (3)	2 (2)	4 (3)	12 (9)
Total	51 (47)	67 (65)	44 (36)	24 (20)	186 (168)

TABLE 2

Total number of days when ≥ 30 knots winds reported by at least one station along the west coast of peninsular India (0000/1200 UTC) during summer monsoon

Year	June	July	August	September	Total
1966	9	21	10	4	44
1971	25	27	24	8	84
1972	13	27	16	7	63
1974	27	29	30	12	98
1975	28	27	25	13	93
1976	19	25	20	8	72
1977	23	28	17	14	82
1979	17	24	18	9	68
1980	29	29	26	7	91
1986	25	25	21	8	79
1987	25	15	15	2	57
1988	24	30	21	17	92
1997	12	29	25	0	66
1998	25	23	14	12	74
1999	20	29	11	2	62
2000	27	24	18	6	75 *
2001	28	25	13	3	69
2002	20	20	18	2	60
2003	19	26	10	1	56 **
2004	18	21	20	9	68
2005	21	27	15	20	83

* 4 days data not available in August

** 7 days data not available in June (1) July (6)

0900 UTC [Fig. 3], 2100 and 0300 UTC (9 September). Heavy rainfall started around 0800 UTC on 09 over Santacruz, 223 mm and 217 mm rainfall amounts were recorded on 10 at 0300 UTC at Santacruz and Colaba respectively.

5.3. *Discussion of 18 June and 23- 26 September 1997 HY rain situations*

Maximum HY rainfall cases have been observed during July followed by June, August and September. Santacruz (Colaba) had recorded 102 mm (123 mm) of rainfall at 0300 UTC on 19th June, 1997 and < 30 kt winds have been reported at 850 hPa along the west coast. A cyclonic circulation up to mid tropospheric level was observed over north west Bay of north-Orissa–west Bengal coast on 18. This is the least synoptic situation observed for occurrence of heavy rainfall over Mumbai. Santacruz (Colaba) recorded 96 mm and 72 mm (132 mm and 107 mm) rainfall at 0300 UTC on 26 and 27 September, 1997. A depression which was centered near 15.5° north 82.5° east on 23 became cyclonic storm on 25 near 17.3º north / 83.7º east about 65 km south-south east of Visakhapatnam. It moved in a north easterly direction and crossed Bangladesh coast in the early morning of 27. However, 850 hPa winds along the west coast did not strengthen (<25 kt). One cyclonic circulation in the lower tropospheric level was observed between 25-26 near east central Arabian sea and adjoining coastal areas of south Konkan and Goa and north Karnataka. So, three cases of heavy rainfall which occurred on 19 June, 26 and 27 September 1997 over Mumbai may not be predicted by the adopted principle.

5.4. *13-14 July 2000 VHY rain situation*

Exceptionally HY rainfall were recorded on 13 and 14 July 2000 at 0300 UTC in north Konkan, Gujarat and

TABLE 3

Number of days ≥ 40 kt (≥ 50 kt) winds observed at 850 hPa along the west coast of peninsular India

Year	June	July	August	September	Total
1966	2 (0)	11 (0)	2 (0)	3 (0)	18 (0)
1971	15 (2)	16 (3)	4 (0)	1 (0)	36 (5)
1972	7 (0)	14 (2)	3 (0)	1 (0)	25 (2)
1974	12 (4)	6 (1)	18 (9)	3 (0)	39 (14)
1975	17 (2)	3 (0)	15 (2)	1 (0)	36 (4)
1976	7 (1)	18 (2)	9 (1)	0 (0)	34 (4)
1977	19 (7)	19 (7)	1 (0)	1 (0)	40 (14)
1979	17 (2)	16 (1)	9 (6)	0 (0)	42 (9)
1980	18 (2)	15 (4)	6 (1)	0 (0)	39 (7)
1986	18 (3)	14 (3)	14 (6)	1 (1)	47 (13)
1987	11 (2)	7 (0)	8 (1)	0 (0)	26 (3)
1988	8 (2)	14 (3)	9 (1)	6 (0)	37 (6)
1997	3 (0)	6 (0)	10 (0)	0 (0)	19 (0)
1998	10 (3)	14 (3)	3 (1)	2 (0)	29 (7)
1999	7 (1)	17 (0)	1 (0)	0 (0)	25 (1)
2000	14 (5)	17 (5)	9 (4)	0 (0)	40 (14)
2001	3 (1)	8 (2)	5 (0)	0 (0)	16 (3)
2002	4 (0)	3 (0)	6 (1)	0 (0)	13 (1)
2003	5 (0)	5 (1)	1 (0)	0 (0)	11 (1)
2004	11 (4)	4 (0)	7 (1)	0 (0)	22 (5)
2005	13 (5)	13 (5)	9 (1)	5 (0)	40 (11)

Kutch region. Upper air observation of 11 at 1200 UTC shows DPD ≤ 5ºC up to 400 hPa (H: 0.7), freezing level 5902 GPM (T: 0.7) and winds (W) are not available. The WTH index comes to 1.4. Upper air observation of 12 (0000 UTC) shows DPD ≥ 15º C from 700 hPa onwards (H:0) freezing level as 5711 GPM (T:0.7) and winds (W) are not available. Upper air observations 12 (1200 UTC) and 13 do not contain winds and freezing levels. This upper air observation does not help much in forecasting HY rainfall over Mumbai and suburbs. The well marked low pressure area was observed over north coastal Orissa and adjoining West Bengal on 12, over northern parts of Madhya Pradesh on13 and as a low pressure area over east Rajasthan and neighbourhood on 14. The cyclonic circulation over Gujarat region and neighbourhood between 2.1 and 4.5/5.8 km continued till 12. The off shore trough was found from south Gujarat coast to Kerala coast from 10-16. LLJ at 850 hPa (30-55 knots) has been found prominent on 12 and 13 from TRV to Goa

TABLE 4

Available 850 hPa winds (≥30 kt) from 02 July 2000 to 14 July 2000 at 0000 UTC along the west coast of peninsular India and 24 hours rainfall recorded over Mumbai (Santacruz/Colaba) at 0300 UTC

July 2000	MNC	TRV	MNG	GOA	Rainfall (mm)
2	25040	27040	-	-	14/30
3	29030*	29030*	-	-	22/21
4	29050	29030	-	29030	195/244
5	28050	29055	-	-	34/64
6	28040	30040	-	-	50/35
7	28050	29040	-	-	62/16
8	-	29040	-	-	186/148
9	29040	27040	-	-	91/81
10	28035	-	-	-	75/91
11	27050	29040	-	27030	08 /15
12	27045	28045	23035*	26030	81/163
13	27055	27040	-	27035 *	351/187
14	27030	29040	-	27030	17 / 06
Total	rainfall				1186/1101

* 1200 UTC Obeservation

[Table 4]. Mumbai has reported < 30 knots wind at 850 hPa between 2 to 14. So The cyclonic vorticity was prominent north of Goa. Santacruz (Colaba) recorded 1186 (1101) mm of rainfall [Table 4] between 2 to 14 July including 6 (7) cases of HY to VHY rainfall.

6. Discussion of all heavy rain occasions (1966 - 2005)

Siji Kumar and Joseph (2001) had observed that during active monsoon periods when there is a band of strong convective heating in the latitude belt of peninsular India from about 70º E to 120° E, Low level Jet (LLJ) axis at 850 hPa passes from central Arabian sea eastwards through peninsular India and emerges into the western Pacific ocean. They have further stated that while the LLJ axis crosses the equator as a southerly current in a geographically fixed and narrow longitudinal band close to the East African coast , the LLJ axis passes through peninsular India as westerly current, but its axis can be anywhere from very low latitude to almost 25° north. Its position changes along the Maximum Cloud Zone (MCZ) in 30-50

days cycle. Reporting of ≥ 50 kt wind along the west coast of peninsular India has not been found frequent during 21 years study period [Table 3]. It has occurred between 0-14 days during the period with a maximum of 14 days during 1974, 1977 and 2000 and a minimum (0 day) during 1997. Heavy rainfall cases occurred over Santacruz (Colaba) during 1974, 1977 and 2000 were 6 (6), 10 (10) and 9 (11) and 6 (10) during 1997 [Table 1]. Santacruz has recorded maximum number of heavy rainfall cases (13) during 1975 and Colaba (15) during 1988. So maximum intensity of 850 hPa wind ≥ 40 kt or ≥ 50 kt along the west coast and occurrence of heavy rainfall over Mumbai does not have one to one relation. It has been observed that when at least one station along the west coast has reported ≥ 30 kt wind at 850 hPa heavy rainfall has occurred over Mumbai in approximately 90 % cases. (171 out of 186 at Santacruz and 150 out of 168 at Colaba). So in 15 (18) cases heavy rainfall have occurred over Santacruz (Colaba) when < 30 kt wind have been reported along the west coast. Out of these, 11 (12) cases of heavy rainfall have occurred over Mumbai during September (73%) .

Number of days when at least one station along the west coast has reported ≥ 30 kt wind at 850 hPa have been counted for selected 21 years period from June to September. The limit for the days when ≥ 30 kt winds have been reported for each of four respective months from June to September is 9-29, 15-30, 10-30 and 0-20 [Table 2] during 21 years period. The year 2005 has been an exceptional year when ≥ 30 kt wind have been reported for 20 days during September and 4 (3) cases of heavy rainfall occurred over Santacruz (Colaba) during the month which is maximum for September during 21 years period [Table 1]. The year 2002 was the only year when HY rainfall did not occur in July [Table 1] over Mumbai. DPD ≤ 5 °C has not been found even up to 700 hPa on most of the days during July 2002 over Mumbai.

7. Conclusion

(*i*) When any station along the west coast of peninsular India from Thiruvananthpuram to Mumbai including Minicoy/Aminidivi islands reports ≥ 30 kt wind at 850 hPa then DPD ≤ 5 °C up to 400 hPa confirms the accumulation of huge moisture for the big event, different wind patterns throw light on the nature of monsoon air mass and help to maintain the attained level of moisture and freezing level under a specific range reveals the condition of the atmosphere at a first glance. These conditions quite significantly reveal about the severe weather conditions likely to hit the station within the next 24 hours.

(*ii*) If 850 hPa wind is weak (<30 kt), heavy rainfall over Mumbai may be forecast in case of movement of any system across the north peninsula/cyclonic circulation over north Konkan or Gujarat region with combined critical value ≥ 1.4.

(*iii*) The methodology discussed in the paper may be useful in forecasting heavy rainfall over Mumbai and suburbs.

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