

Synoptic systems associated with onset of southwest monsoon over Rajasthan

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सार – इस शोध-पत्र में मानसूनी हवाओं के रूख से संबंधित अल्पावधि पूर्वानुमान के क्षेत्र में आधुनिक प्रेक्षणत्मक प्रौद्योगिकी और विकसित पूर्वानुमान तकनीक के आधार पर वर्ष 1971–2004 की अवधि के लिए पूर्वी और पश्चिमी राजस्थान के दो मौसम वैज्ञानिक उपखंडों में दक्षिणी-पश्चिमी मानसून के आगमन के लिए उत्तरदायी प्रमुख सिनॉप्टिक विशेषताओं का पता लगाने का प्रयास किया गया है। अरब सागर में उत्पन्न हुई निम्न दाब प्रणालियों (एल. पी. एस.) से प्रमुख रूप से मध्य क्षोभमंडल का केंद्र (एम. टी. सी.) बनता है जिससे मानसून आगमन के पूर्वानुमान के लिए अच्छे संकेत मिलते हैं जो राजस्थान में ग्रीष्मकालीन मानसून के आगमन का सुस्पष्ट लक्षण है। इसके अतिरिक्त बंगाल की खाड़ी में बनी निम्न दाब प्रणालियाँ पश्चिम से उत्तरी पश्चिमाभिमुखी दिशा में आगे बढ़ती हुई निम्न दाब क्षेत्र के रूप में अथवा उपरितन वायु चक्रवाती परिसंचरण के रूप में राजस्थान और इसके निकटवर्ती क्षेत्रों में पहुँचती हैं जिनके कारण राजस्थान में भी मानसून का आगमन होता है।

ABSTRACT. An attempt has been made to identify the main synoptic features, which are responsible for onset of southwest monsoon over the two met sub divisions east and west Rajasthan for the period 1971–2004 based on modern observational technology and developed forecasting technique in the field of short-range prediction of monsoon surges. The low pressure systems (LPS) originate over Arabian Sea, especially the formation of MTC which indicates a good signature for predicting onset of monsoon, which is the prominent feature for causing onset of summer monsoon over Rajasthan. In addition LPSs form over Bay of Bengal moved in west to northwestwards direction and reach over Rajasthan and its neighbourhood region as a lopar or an upper air cycir, also brings monsoon over Rajasthan.

Key words – Synoptic features, Monsoon disturbances, Monsoon surge, Air masses, Low pressure systems (LPS), MTC, Onset.

1. Introduction

Intensive study has been made on the onset of southwest monsoon for over more than four decades. Concerted efforts have been made in recent years to look into various aspects of the monsoon dynamics. Godbole (1977) studied structure and movement of the monsoon depression. Dasgugpathy and Sikka (1977) found that westward movement of monsoon depression is due to production of vorticity in western sector. Murakami (1977) made spectrum analysis of monsoon lows while Sarkar and Chowdhury (1988) had a diagnostic study of monsoon depression. Dates of onset of monsoon and its associated features have been studied by Ramamurthy and Keshavamurthy (1964) and Subramayya *et al.* (1984). Defining and declaring onset of monsoon at a place, unequivocally is to be set with difficulties. It depends upon the interest in view. A synoptician would look into the prevailing air mass characteristics; a hydrologist would prefer cumulative rainfall in a fixed period of time and an agriculturist on distribution of rainfall for fixing onset date for a place. The criteria for onset of monsoon is

not unique and realistic, Raman (1974). It is difficult to declare onset of summer monsoon over the area of Rajasthan, which is a part of Thar Desert and sustained rainfall of significant amount, seems to be rare there. Despite numerous studies undertaken on monsoon disturbances, knowledge on the subject is essential on regional scale also to solve out the problem up to certain extent for declaring onset of summer monsoon based on synoptic data analysis specially over Rajasthan which is lowest rain fed area. A possible reason for desert and semi arid conditions are characterised by the marked absence of rain generating weather systems, however monsoonal winds prevail over Rajasthan every year between June-September causing inflow of humid air streams. Sengupta (1986) studied synoptically some cases, which caused localized floods in Rajasthan due to exceedingly heavy rain associated with intense upper air anti cyclonic circulation. Ganeshan and Prasad (1985) examined synoptic features responsible for the occurrence of heavy spells in and around Jaipur. Gupta (1984) discussed unprecedented floods in south Rajasthan in July. Mukherjee and Shyamla (1977) evaluated distant effects

of monsoon depression over west Rajasthan. Wide spread rain do occur in the monsoon season associated with low pressure systems and orography of the region etc. as also in association with western disturbances and upper air westerly waves activating monsoon lows and quite often ushering advancement of monsoon over Rajasthan. The advance of monsoon does not take place progressively only in one spell once monsoon has set advance in the Andamans or Kerala but its northward movement take place in a few spells in the form of monsoon surges (Rao, 1976). Such surges can be seen in the form of monsoon disturbances. The aim of the present study is to identify these main synoptic features, which cause onset over east (west) Rajasthan for the period 1971-2004. The main objective of this study is to extend the knowledge on synoptic aspects of the monsoon, which is still backbone of the weather forecasting especially over Rajasthan region where the monsoon sets in the country. The surge, which develops into the Bay and reaches to the Rajasthan region, the study of such cases presents scenario of the system from beginning to the end. Intense monsoon disturbances cause heavy rain over Rajasthan inspite of stagnation of the semi permanent system heat low there.

2. Data

The onset dates of monsoon over east (west) Rajasthan along with the antecedent synoptic situations were extracted from IDWR/IWWR, carefully examined all available observational data including related satellite images analysed critically to identify the synoptic features responsible for onset of summer monsoon over Rajasthan. Vorticity and divergence fields were collected from RSMC, New Delhi. Related INSAT cloud imageries were taken from the DGM's office, New Delhi.

3. General features of Topography and monsoon circulation over Rajasthan

The Rajasthan state lies roughly between 23° N and 30° N Latitude and 69° E & 78° E Longitude. The state has a very dry climate, which is primarily influenced by the Aravali range dividing the state into two parts, western part forming "great desert" extends from Rann of Kutch to near Delhi, features frequent dust storms and scanty rainfall. Its eastern side is little desert consisting of rocky land cut off by lime stone ridges, which to some extent protect it from the desert sandy climates determined by Aravalli range. West Rajasthan has tropical desert arid & hot climate with temperature varying appreciably from morning to evening whereas the remaining part has tropical steppe, semi arid a hot climate. The annual rainfall is 15 cm (75-100 cm) in the west (east) Rajasthan of which 75-80% rainfall is received during monsoon season (Climate of Rajasthan State, 1988).

Das (1995) studied the circulation patterns over India for July, found that monsoon circulation over India was dominated by two principal zones, one of which represented ascending currents of air over northeastern states and zone of descending air over northwest India specially near the area of Rajasthan desert (a branch of walker circulation).

The air mass ordinarily present over the desert area during the monsoon season are (i) moist southwesterly to westerly monsoon air from Arabian sea between the surface and about 1.0 km as a result of cross equatorial flow (ii) the warm air and dry air from west and north *i.e.*, from Baluchistan and northwest frontier side between about 1 and 4 km blowing over great desert which gives rise to stable condition or an inversion (Das, 1995) (iii) dry continental air from a direction between north & east over the northern parts between about 4 & 6 km. The stable conditions which are produced at about 1.5 km. a.s.l. *i.e.*, over the area ordinarily prevent formation of clouds and rain. If due to, monsoon disturbances which move from the north Bay of Bengal or Arabian sea towards and across the area, and the lows which develop over there or some other synoptic situations by which the dry continental air mass at about 1.5 km is replaced by moist air mass, considerable rain can occur due to convergence of different air currents or the moist air mass rising over the cooled moist air. It may be stated that considerable rain over the desert area occurs due to this mechanism and the heavy rain and floods, which occurs at times during the monsoon season over the desert area of Rajasthan, are due to such causes Sengupta (1986). In addition, it is well known that in the absence of depression or low when the monsoon trough is active, light to moderate rain occurs over a strip of 200-300 km wide to the south of axis of the trough at the surface. This rain occurs due to convergence at the trough axis and the up glide action (Desai, 1970). Thus despite of heat low and monsoon trough little rain occurs there due to natural causes of topography and of the distribution of different air masses over the area.

4. Discussion of analysis

It is usually observed that the first surge, which brings monsoon current over Kerala, is insufficient to maintain its continuous northward movement to cover huge land mass area and to reach northwestern parts of the country up to Rajasthan. For its further northwards progress a fresh surge is essentially required which can be visualized in the day-to-day synoptic charts (Rao, 1976). The synoptic situations, which are responsible for onset over Rajasthan, have been noted. Table 1 presents the synoptic features that causes onset of southwest monsoon over east and west Rajasthan during 1971-2004. These

TABLE 1

Synoptic situations associated with onset over Rajasthan

Year	East Rajasthan Onset date / Synoptic situations	West Rajasthan Onset date / Synoptic situations
(1)	(2)	(3)
1971	<p>24 June</p> <ol style="list-style-type: none"> 1. Depression (Dep.) over Bay crossed coast and on 23 June centered near Narsinghpur and weakened as lopar over west (W) Madhya Pradesh (M.P) and neighbourhood (n'hood) on 24 Jun., associated (asso.) cycir upto mid-troposphere level (MTL) 2. Lopar at Gulf of Cambay 3. Axis : Bikaner (BKN)-Sagar-Head Bay 	<p>26 June</p> <ol style="list-style-type: none"> 1. Bay depression weakened and reached to west (W) M.P as lopar and merged with Seasonal Trough (S.T.) on 25th associated cycir over northwest (NW) M.P and neighbourhood upto 2.1 km. a.s.l. 2. A lopar over central Uttar Pradesh (U.P.) and neighbourhood, associated cycir up to MTL 3. Axis : Ganganagar (GGN)-southeast (SE)- Bay through Agara-Gaya-Calcutta (CAL)-Bay
1972	<p>26 June</p> <ol style="list-style-type: none"> 1. Depression (Dep.) over northeast (NE) - Arabian sea (A.sea) (21.5° N / 67.5° E) during 25-27 June, asso. cycir upto 7.6 km a.s.l. 2. Monsoon axis at normal position 3. Lopar over Himachal Pradesh (H.P.) n'hood (WD) 	<p>30 June</p> <ol style="list-style-type: none"> 1. Depression over A.sea during (25-27 June) weakened there into a feeble low on 30th, asso. cycir upto 7.6 km. a.s.l. 2. Well Marked (WM) lopar over Saurashtra & adj. Konkan, asso. cycir upto MTL 3. Bay low move to NE-M.P. & n'hood 4. Low over NW-Bay & adj. Orissa
1973	<p>5 July</p> <ol style="list-style-type: none"> 1. Low over Bay on 4th July, Dep. over Bay on 5 July, asso. cycir upto MTL 2. W.D movement 	<p>6 July</p> <ol style="list-style-type: none"> 1. Dep. over Bay on 5-6 July, asso. cycir upto MTL 2. Low over south (S)-Gujarat & adj. east central (EC) A. sea, asso. cycir upto MTL 3. W.D movement
1974	<p>11 July</p> <ol style="list-style-type: none"> 1. Low over EC-Pakistan (Pak) & adj. Rajasthan (Raj.), asso. cycir upto MTL (WD) 2. Feeble low over north (N) - M.P. & adj. S-U.P, asso. cycir upto MTL 3. Monsoon axis BKR-Chittugam-Jhansi-Ranchi (RNC)-Bay 	<p>12 July</p> <ol style="list-style-type: none"> 1. Extended low over central (C)-Uttar Pradesh (U.P) & adj. northwest (NW) - M.P. asso. cycir upto MTL 2. MTC 3. Induced low over Rajasthan (Raj.) & neighbourhood (WD) 4. Axis : GGN-CHT-RNC to Bay
1975	<p>23 June</p> <ol style="list-style-type: none"> 1. Dep. over Bay during 18-19 June moved-weakened & as a low over NW-U.P & neighbourhood, asso. cycir upto 4.5 km. a.s.l. 2. WM low formed over S-Gujarat (Guj.) & adj NE-A. sea, asso. cycir upto 7.6 km. a.s.l. 	<p>29 June</p> <ol style="list-style-type: none"> 1. WM low over A. sea on 23/6, Dep. on during 24-27 June 2. Dep. over Bay on 26 June -> weakened in land & moved & over SW-UP neighbourhood on 29/6, asso. cycir upto MTL 3. Seasonal low WM over west (W)-Raj
1976	<p>11 July</p> <ol style="list-style-type: none"> 1. Cycir over NW Raj. & adj. Punjab on 11/7 (WD) 2. Trough along 20° N at MTL 3. Lopar over Bangladesh, cycir upto 7.6 km. a.s.l. 4. Axis : Anupgarh (ANP)-Gawalior (GWL)-Hazaribagh-lopar 	<p>15 July</p> <ol style="list-style-type: none"> 1. MTC between 3.1 to 7.6 km a.s.l. over Guj., adj. S-Raj & adj. NW-M.P 2. Cycir over Bangladesh & neighbourhood up to 7.6 km. a.s.l. 3. WM seasonal trough axis ; BKR-Sikar (SKR)-GWL-Gaya (GYA) – Digboi

TABLE 1 (Contd.)

(1)	(2)	(3)
1977	29 June	30 June
	1. Dep over Bay during 15-22, weakened-WM lopar on 24/6, moved to S-Raj. and adj. Guj. on 29 th , asso. cycir upto 7.6 km. a.s.l.	1. Lopar over W-Raj on 29 th merged with seasonal trough (S.T.)
	2. A lopar over Bihar & adj. Gangetic West Bengal (GWB) on 29/6, asso. cycir upto MTL	2. Low over Bihar & low over S-U.P, combined cycir upto 4.5 km. a.s.l.
	3. Axis : Barmer (BRM)-Jhansi-DTG-Contai-southeast (SE) – Bay	3. Axis : BRM-Ajmer-Allahabad-RNC-Contai-Bay
1978	22 June	3 July
	1. WM low over Bay moved to Bihar & adj. NE-M.P on 22 June, cycir upto 4.5 km. a.s.l.	1. Lopar over Bay moved & merged with low over Pendra, concentrated into Dep. on 1 st July- weakened – as a lopar over NW-M.P & adj. S-Raj on 2 nd -> low over C-Raj. on 3 rd , asso. cycir upto MTL system live (30 June to 3 July)
	2. Well marked MTC over Guj & adj. S-Raj NW-M.P upto MTL	2. WD moving over J&K & neighbourhood
	3. Lopar over A. sea on 20-21 June weakened as trough 68° E on 22 June	3. Axis : ANP-Kota-Riwan-CAL-Bay
	4. Lopar over Bay 19° N / 87° E formed on 20 June	
1979	11 July	15 July
	1. Lopar over NE Bay-4 th , Dep. on 7 th to 8 th July-> lopar over NW-M.P & adj. S-Raj on 10 th -> merged with S.T. on 11/7, asso.cycir upto MTL	1. Remanants of Bay Depression formed over Bay on 7 th , as upper air cycir over NW-MP, adj. Raj. & adj. S-U.P during 12-14 Jul. -> intensified & formed lopar over NE-Raj, asso. Cycir upto MTL
	2. Lopar over EC-Bay & adj. NE-Bay on 11 th July	2. Axis: ANP-AGR-PTN-Pasighat
	3. WD movement	3. WD (12 to 15 July) (monsoon vigorous over E-Raj.)
1980	26 June	28 June
	1. Feeble low over Bay on 12 Jun, moved, formed Dep. on 19 June over Orissa & adj. Bay, moved to M.P on 22 nd , on 23 over S-Raj as lopar->on 24 June over NE-A sea, on 25 June intensified into Dep. over Arabian sea, move westward on 26 centered near Oman coast	1. Cycir over GWB & adj. Bihar on 26 Jun, moved, intensified in to lopar over NE- M.P. & neighbourhood on 27 Jun., under its influence lopar formed over SW- Raj & adj. N- Guj on 27 th , asso. cycir up to MTL
	2. Another WM low over Bay on 22 Jun., moved, over NE – M.P & adj. U.P., & merged with S.T. on 26 June	2. WM low over Bay on 28 th
	3. Upper air cycir over N-Pakistan (Pak) with associated trough in Mid trop. level in westerly (W ^{ly}) at 68° E north of 25° N (WD)	3. Axis at 0.9 km a.s.l.: Jaisalmer - Tonk –Allahbad- Daltonganj- Calcutta-Bay
		4. WD movement
1981	29 June	10 July
	1. Dep. over Bay on 20 Jun., crossed coast, moved, on 24 June Dep. over C-M.P; weakened –as a lopar over NW-M.P.& adj.Raj. merged with S.T.; u/a cycir moved to NE –Arabian sea & adj. Saurashtra & Kutch on 28 th June	1. WM low over Head Bay on 6 Jul., moved over C-M.P on 9 th ; over E-Raj & adj. M.P ; as a lopar over S-Raj & adj. S-Pak. on 10 th
	2. MTC between 2.1 to 5.8 km. a.s.l.	2. Trough at 65° E / 30° N in Westerly
	3. Seasonal low well marked	3. Well marked axis passes through – Barmer-Nimuch-Sagar-Ambikapur-Bay
	4. WD movement	

TABLE 1 (Contd.)

(1)	(2)	(3)
1982	14 July	22 July
	1. Lopar over S-U.P. & neighbourhood moved to NE-Raj & adj. M.P on 13 -14 July, asso. cycir up to 3.1 km a.s.l.	1. Dep. over Bay on 18th Jul.–Deep Dep. On 19 th July & crossed coast on 19 th - weakened – as a lopar over NW-M.P SW-U.P. & adj. SE-Raj. on 21 st Jul, moved & weakened –as an u/a cycir over N-Raj , merged with S.T. on 22 July System live (18-21 July)
	2. WM lopar over Saurashtra & Kutch as asso. cycir up to MTL	2. Cycir over Saurashtra & Kutch upto MTL
	3. Axis : Bhatinda-Delhi-Kanpur-Balasore-Bay	3. Axis : Phalodi-Gwalior-Daltonganj-Calcutta-Bay
		4. WD movement 19-22 July
1983	4 July	18 July
	1. Lopar on 22/6 over NW Bay – Deep Depression Over Bay on 24, crossed coast on 25 June, on 27 Dep. over N-Orissa, on 28 WM lopar S-U.P & adj. N–M.P., on 29 June over SW-U.P & adj. NE-Raj. as WM lopar over S-Raj. on 30 June - as lopar over S-Raj. & neighbourhood on 1 July- as a lopar over Punjab & adj. H.P during 3-7 July, less marked on 4 July	1. Lopar over NW –Bay on 7 th –moved - Vidharbha – to –SW-M.P - to– SE-Raj- & adj. N Guj. to W-Raj on 15 th July merged with seasonal trough (S.T.)
	2. Cycir over W-Raj & adj. Pak – upto 3.6 km a.s.l. (WD)	2. Cycir over SE- Pak to W-Raj. upto 3.1 km a.s.l. (WD)
	3. Trough of 9.5 km a.s.l. runs from J & K roughly along 75° E north of 25° N	3. Cycir over NW-Bay between 1.5- 5.8 km a.s.l.
		4. Well Marked Axis: ANP-Gurgaon-RNC-Tura-Calcutta-Bay
1984	4 July	6 July
	1. Lopar over GWB & adj. Orissa on 29 June – Dep. on 30 June-moved-to land; over NE-M.P & adj. SE- U.P on 3 July, on 4 July over NE-Raj. & adj. SW-U.P, asso. cycir upto 4.5 km. a.s.l.	1. Lopar over GWB & adj. Orissa on 29 Jun, Dep. On 30 June-moved-over SW U.P & adj. NE- Raj on 4th July, merged with seasonal trough on 5 July
	2. MTC between 3.1 to 5.8 km. a.s.l.	2. MTC over Guj – N –Maharashtra & adj. W-M.P during 2-6 July
	3. U/A cycir over Haryana & neighbourhood upto 1.5 km a.s.l. (WD movement)	3. Cycir over NW-Bay on 4 July, moved to N-M.P. & adj. U.P. on 5-6 July up to MTL
		4. Low level circulation over C-Pak & adj. W-Raj. on 5 th
		5. Cycir over N-Pak adj. J&K, trough at 7.6 km.a.s.l.
1985	14 July	14 July
	1. Cycir developed over NW MP & adj Raj. on 11 th , moved to- NW Raj. adj. Haryana on 14 th evening	1. Cycir developed over NW MP & adj. Raj on 11 th , moved NW-over NW Raj & adj. Haryana on 14 th evening
	2. MTC over Saurashtra & Kutch & adj. NE -Arabian sea between 2.1 – 3.6 km. a.s.l.	2. MTC over Saurashtra & Kutch & adj. NE- Arabian sea between 2.1 – 3.6 km a.s.l.
	3. Cycir over C-Pak Punjab & adj. NW Raj on 11 th merged with S.T on 14 th	3. Cycir over C-Pak Punjab & adj. NW Raj on 11 th merged with S.T on 14 th
	4. Cycir over N-Raj. & neighbourhood between 1.5 to 5.8 km. a.s.l.	4. Cycir over N-Raj & neighbourhood between 1.5 to 5.8 km. a.s.l.
1986	24 June	24 July
	1. Lopar over NW-Bay moved and less marked over E-M.P on 22 June - cycir moved to NW-M.P on 23 June - less marked on 24 June	1. Low over WC & adj. NW Bay, to North C-A.P. & adj. S-Orissa on 17 July, WM low over Bihar & adj. GWB on 21 July – Dep. on 22 th over N-M.P. (Pendra), on 23 June weakened, WM low over NW-MP on 23 evening, move to SW-U.P. & adj. Raj. on 25 July 1986 as a lopar
	2. Cycir over NW-Raj & adj. Punjab in lower level on 24 - 25 Jun (WD)	2. Trough along 30° N / 69° E at 500 hPa in westerly wind
	3. MTC between 2.1 – 7.6 km a.s.l. on 23 June 1986	
	4. Another lopar over N-Orissa & neighbourhood with cycir up to MTL on 24 June	

TABLE 1 (Contd.)

(1)	(2)	(3)
1987	15 July 1. Lopar over GWB & adj. Orissa- on 12 th July, weakened-move -to- S-U.P. & adj. N-M.P. on 14 th , as a cycir in lower level over W-U.P. adj. Raj. on 15 th 2. MTC during 11-14 July	27 July 1. Cycir over N-Pak moved to Punjab & neighbourhood in lower level (WD) 2. MTC on 26 th between 4.5-5.8 km a.s.l. 3. Cycir over SW-U.P. & adj. NW-MP -adj. Raj. 4. Trough in W'ly north of 30° N - 72° E at (9.5 km. a.s.l.)
1988	30 June 1. Lopar over GWB & adj. Bihar on 27 June - moved - over NE -Raj. S. & neighbourhood on 30 June as lopar, asso. cycir upto MTL 2. MTC between 1.5 - 3.6 km. a.s.l.	1 July 1. Lopar over GWB & adj. Bihar 27 June - moved-over NE -Raj. on 30 June, asso. cycir upto MTL 2. MTC between 1.5 - 3.6 km a.s.l.
1989	1 July 1. WM low over NW-Bay on 27 Jun-moved -weakened - as lopar over SE-M.P & adj. Orissa on 28June ->as cycir over NW-M.P. & adj. Raj. upto 3.1 km a.s.l. 2. Feeble low over Haryana & adj NE -Raj., asso. cycir in lower level (WD) 3. MTC on 30 June	2 July 1. WM - low over NW-Bay 27 June-moved-weakened - as a lopar over SE-M.P. & adj. Orissa on 28 Jun -> as a cycir on 29 June over NW-M.P & adj. Raj. upto 3.1 km a.s.l. 2. Feeble low over Haryana & adj. NE -Raj., asso. cycir in lower level (WD)
1990	28 June 1. WM -low over Bihar plateau & neighbourhood on 28 from Bay, asso. cycir upto MTL 2. Lopar over Gulf of Cambay 3. MTC between 1.5 - 4.5 km a.s.l. 4. WD movement	1 July 1. WM -low over NW-Bay on 26 June, over Bihar & neighbourhood on 28 June moved and as a lopar over N-M.P. - & adj. S-UP on 30 th , asso. cycir upto MTL 2. MTC between 3.1-5.8 km a.s.l. 3. WD movement
1991	16 July 1. WM lopar over Bay, asso. cycir. upto MTL 2. MTC 3. Cycir. over N-Raj. & neighbourhood upto 1.5 km a.s.l. 4. Axis : BKR- GWL-Bay lopar 5. Ridge along 32° N at 300 hPa 6. Feeble low over SE-Raj. asso. Cycir. upto 1.5 km a.s.l. (W.D.)	19 July 1. WM Lopar over Bay on 16 July -moved - on 19 July over W-M.P. & adj Raj . asso. Cycir. upto 3.6 km a.s.l. 2. WM seasonal low 3. Cycir over N-Pak.& adj. Raj. upto 1.5 km a.s.l. 4. MTC 5. Axis : Bikaner-Kanpur-Daltonganj-Bay
1992	12 July 1. Lopar over Bay on 10 th July, moved and on 12 July over C-U.P. & adj. M.P., asso. cycir. upto 3.1 km a.s.l. 2. Cycir over NW-Raj. in lower level 3. MTC	14 July 1. Lopar over Bay on 10 th move and over C-U.P. & adj. M.P. asso. cycir upto 3.1 km a.s.l. 2. Cycir over NW-Raj in lower level 3. MTC
1993	27 June 1. Lopar over GWB & adj. Bihar on 24 June, cycir upto MTL, over, N-M.P. & adj. SE-U.P. on 27 June, cycir upto MTL 2. MTC between 3.1 - 4.5 km a.s.l. 3. WD over N-Pak and neighbourhood 4. Trough Punjab to MP in lower level	5 July 1. Lopar over NE-Arabian sea on 4 July; moved & over Saurashtra on 5 July, asso. cycir upto MTL 2. Cycir over W-Raj. in lower level 3. MTC on 4 th merged with S.T. on 5 th July

TABLE 1 (Contd.)

(1)	(2)	(3)
1994	27 June	30 June
	1. Lopar over NW-Bay on 26-27 June, asso. cycir upto MTL	1. Lopar over Bay On 26-27 June moved to SE-U.P. & adj. NW-M.P. and UP on 30 June, asso. cycir upto MTL move to Raj. on 1-2 July system live (26 June - 2 July)
	2. Trough in lower level from W-Raj. to WM Lopar over Bay	2. WD movement
	3. East-West trough over Saurashtra N- Orissa between 3.1 – 5.8 km a.s.l. during 24-28 June	
1995	13 July	13 July
	1. Cycir over Haryana, adj. NE-Raj. upto 1.5 km a.s.l. (WD)	1. Cycir over Haryana & adj. NE-Raj. upto 1.5. km a.s.l.
	2. MTC over S-Gujarat & neighbourhood between 2.1-5.8 km a.s.l.	2. MTC between 2.1 & 5.8 km a.s.l.
	3. Lopar over NW-Bay off Orissa coast	3. Lopar over NW-Bay off Orissa coast
	4. Axis BKN-GWL-RNC-Sagar to Lopar	4. Axis : BKN-GWL-RNC-SGR to Bay lopar
1996	22 June	30 June
	1. WM lopar over EC-Arabian sea, Dep. - on 17 evening, Deep Dep. on 18 June morning, – Cyclonic Storm on 18 evening, – Severe Cyclonic Storm on 18 night – crossed S- Gujarat coast Veraval on 19 morning- weakened– Deep Dep.on 20 morning near Deesa, as WM lopar over SW-Raj. & neighbourhood on 20 June evening, lopar over Haryana & neighbourhood on 22-23,over W-U.P. & neighbourhood on 24-25 June, less marked on 26 June	1. Cycir over Hayana and adj. in lower level (WD)
	2. Lopar over GWB & n'hood with cycir upto MTL on 21-23 June (monsoon reached upto Barmer-Phalodi-Sikar-Nagaur on 24 June)	2. Well marked seasonal low, asso. trough at 850 hPa
		3. Trough in westerly along 25-30° N / 75° E at 500 hPa
		4. Cycir over Bihar & neighbourhood up to MTL
		5. Axis : BKR-ALW-to foothills
1997	9 July	19 July
	1. MTC between 3.1 – 5.8 km a.s.l.	1. Cycir over Gujarat neighbourhood upto MTL
	2. Cycir over SW-Raj & adj. Pakistan in lower level on 6-7 July, on 9 th over Punjab & neighbourhood 1.5 (WD) (monsoon on 10 th - Churu, on 12 th Barmer-Ganganagar)	2. Cycir over Punjab & H.P. in lower level
1998	30 June	30 June
	1. Cycir over S-Raj. adj. Pak during 27-29 June (WD) move on 30 Jun. to Haryana & neighbourhood upto 3.1 km a.s.l.	1. Cycir over S-Raj. adj. Pak during 27-29 June (WD) move on 30 June to Haryana & neighbourhood upto 3.1 km a.s.l..
	2. MTC between 3.1-7.6 km	2. MTC between 3.1-7.6 km a.s.l.
1999	22 June	12 July
	1. Deep Depression (DD) over Bay, on 17 midnight crossed Gopalpur, moved and weakened & as a lopar over West-M.P. & neighbourhood on 21 Jun, asso. cycir up to 2.1 km a.s.l.	1. Cycir over Punjab moved to Haryana & adj. Raj.
	2. Cycir over S-Raj. & adj Pak. during 18-22 June moved to Haryana & neighbourhood, cycir upto MTL	2. Cycir over Pak, Punjab & neighbourhood up to 2.1 km. a.s.l. on 12 th July
	3. MTC between 3.1-7.6 km a.s.l.	3. Cycir over Saurashtra & n'hood on 9 th less marked on 10 th July

TABLE 1 (Contd.)

(1)	(2)	(3)
2000	30 June	2 July
	1. Lopar over Bay moved to East Vidarbha & neighbourhood on 30 June, asso. cycir upto MTL	1. Lopar <i>in situ</i> over E-Raj. & neighbourhood, asso. cycir up to MTL – less marked on 2 July (Cycir over South Vidarbha & neighbourhood merged with S.T. on 2 July)
	2. MTC over Guj., Konkan & neighbourhood during June-2 July	2. MTC between 2.1 - 4.5 km a.s.l.
	3. Cycir over Jammu & Kashmir & neighbourhood upto 2.1 km a.s.l.	
	4. Axis : Bikaner-Kot-Raipur-Kalingapatnam-Bay	
2001	24 June	3 July
	1. Cycir over S-Pak. & neighbourhood on 21 June to 23 June - over NW-Raj.& adj. Punjab on 24 - 25 June, (WD)	1. Cycir up to MTL over NW-Bay on 28 June - move to Orissa – to - C-M.P. - to – NW-M.P. to E-Raj. on 3-July
	2. Axis : ANP-Alwar-Kanpur-Allahabad-Daltanganj-Bay	2. Cycir over N-Pak. & adj. Punjab persists till 2 nd (WD)
		3. MTC
2002	19 July	15 August
	1. U/A cycir over N-Pak. & adj. J&K upto 2.1 km a.s.l.	1. Cycir over Punjab & adj. Haryana on 15 th August
	2. Lopar over NW-Bay off Orissa coast on 18 th – over Chattisgarh on 19 th – Less marked on 20 July asso.cycir up to MTL	2. Cycir over C-Pak. & adj. Punjab up to MTL
		3. Cycir over Jharkhand to NW-MP- & E-Raj. up to MTL
		4. Axis: ANP-Dholpur- Satana- Jamshedpur-Bay
2003	5 July	5 July
	1. MTC between 1.5-5.8 km a.s.l. during 3-6 July	1. MTC between 1.5-5.8 km a.s.l. from 3-6 July
	2. Lopar over WC and adj NW-Bay off N-Andhra., S-Orissa coast on 5 th	2. Lopar over WC and adj NW-Bay off N-AP, S-Orissa coast on 5 th
	3. Cycir ove NW-Raj.& neighbourhood upto 2.1 km a.s.l.	3. Cycir over NW-Raj.& neighbourhood upto 2.1 km a.s.l.
	4. Axis:Phalodi-Udaipur- Bhopal- Raipur- lopar over Bay	4. Axis : Phalodi-Udaipur-Bhopal-Raipur-Bay lopar
2004	5 July	18 July
	1. Lopar over Bay moved & lay over Chhatisgarh & associated cycir between 1.5 km & 4.5 km a.s.l.	1. Cycir over N - Raj. upto 2.1 km a.s.l.
	2. MTC	2. Low at 500 hPa over N-Raj.
	3. Cycir over NW-Raj. & neighbourhood upto 2.1 km a.s.l.	3. MTC between 2.1 & 4.5 km a.s.l.
	4. Axis : FZP-Hisar-Orai-Jamshedpur- thence southeastwards to Bay	4. Axis : FZP-Dehradun-to foot hills. (monsoon active over E-Raj.)

Axis represents the position of monsoon trough on sea level chart

were carefully examined and grouped in various categories as shown in Table 2. These categories are as follows.

Type I – Incursion of Bay of Bengal current

The low pressure systems (LPS) (lopar, Depression, C.S.) formed over Bay of Bengal play a notable role during monsoon season. These produce rainfall over a

wide area through convergence and vertical motion associated with them. A large proportion of these LPS formed over Bay crossing coast move across north and central India in a direction between west and northwest and reached mostly over northwest Madhya Pradesh and adjoining Rajasthan or Rajasthan either as an upper air cycir or on some occasion as lopar and rarely as depression, generally weakened in their movement over huge land area thereby extended the Bay currents of

TABLE 2

Frequencies of main synoptic situations responsible for onset over Rajasthan

Category	Main synoptic situations prevailed during onset of monsoon	Year		ER (WR) (%)		
		ER	WR			
I	<i>System originating over Bay or adjoining land areas</i>					
A	Depression/Deep Depression move northwest/north-northwest ward and weakened and reached as LOPAR/upper air cycir over northwest M.P. and adj. Rajasthan or Rajasthan	1971 ^{al} , 1979 ^w , 1983 ^w	1975 ^{alw} , 1980 ^{waD} , 1984 ^{mw} , 1987 ^l , 1981 ^{mw} , 1999 ^{mw}	1971 ^a , 1977 ^l , 1979 ^{Rw} , 1982 ^w , 1984 ^{lmwR}	26 (18)	
B	Well marked lopar/lopar moved and weakened and reached over northwest M.P. and adj. Rajasthan or Rajasthan as a LOPAR/upper air cycir	1986 ^{mw} , 1989 ^{mw}	1987 ^m , 1988 ^m	1978, 1981 ^w , 1983 ^w , 1986 ^{DRw} , 1988 ^{mw} , 1989 ^m , 1990 ^{mw} , 1991 ^m , 1994 ^w	12 (26)	
II	<i>System originating over Arabian sea</i>					
A	Depression/Cyclone	1972 ^w , 1996 ^C	(2)	1972 ^{bl}	6 (3)	
B	Lopar	1978 ^m , 1982 ^w	(2)	1973 ^{Dw} , 1993 ^{mw}	6 (6)	
C	MTC	1985 ^w , 1992 ^w , 1997 ^b , 2002 ^{blw}	1990 ^w , 1993 ^{lw} , 1998 ^w , 2003 ^{bl}	1991 ^{bl} , 1995 ^{bl} , 2000 ^w , 2004 ^{blw}	1974, 1976 ^l , 1985, 1987, 1992, 1995 ^{blw} , 1997 ^{bl} , 1998 ^w , 2001 ^w , 2003 ^{blw} , 2004 ^w	35 (32)
III	<i>Western disturbances/induced u/a cycir over north Raj. and adj. areas</i>	1973 ^D , 2001	1974 ^l , 1976, 1994 ^l	1996, 1999, 2002	15 (9)	
IV	<i>Lopar in situ</i>		(5)	1980 ^{blw} , 2000 ^w	0 (6)	

Superscript (m : mid tropospheric cycir; w : western disturbance; bl : low pressure over Bay; C : Cyclone, D : depression over Bay; al : lopar in Arabian sea)

monsoon over Rajasthan. Thus the system originates over northwest Bay of Bengal, once moved over southeast Rajasthan as a weak system, is strengthened there due to moisture feed from Arabian sea and gives good rainfall over Rajasthan. These are further subdivided in to two categories *Type IA* - Depression / Deep Depression and *Type IIB* low pressure area from Bay of Bengal (Table 2). Their contribution is found on 38 (44)% occasions for onset over east (west) Rajasthan. In some other cases (in 1991, 1995, 2002, 2003 and 2004 etc. for east-Rajasthan & in 1995, 1997, 2003 etc. for west Rajasthan) the formation of LPS over Bay or in adjoining land area with its associated cyclonic circulation bring about the confluence of easterlies and westerlies over Rajasthan & neighbourhood along with other types of monsoon disturbances there (Table 2).

Type II - Incursion of Arabian Sea current

The LPS formed over Arabian Sea are further categorized into three parts.

Type-IIA Depression /Cyclonic storm

Type-IIB Low pressure area

Type-IIC Formation of mid tropospheric circulation (MTC) (Table 2) activate Arabian Sea branch of monsoon over Rajasthan. MTC generally formed over northeast Arabian Sea adjoining Gujarat and west coast, causing cupious rainfall over the region in its life span during monsoon season. These cyclonic vortices are confined to middle troposphere and hardly seen at the sea level charts, also not seen in the wind field at the upper troposphere levels. These are confined to middle troposphere between the levels 700-500 hPa and have maximum intensity near 600 hPa. These are called cold core lows below 4 km a.s.l. and warm core lows

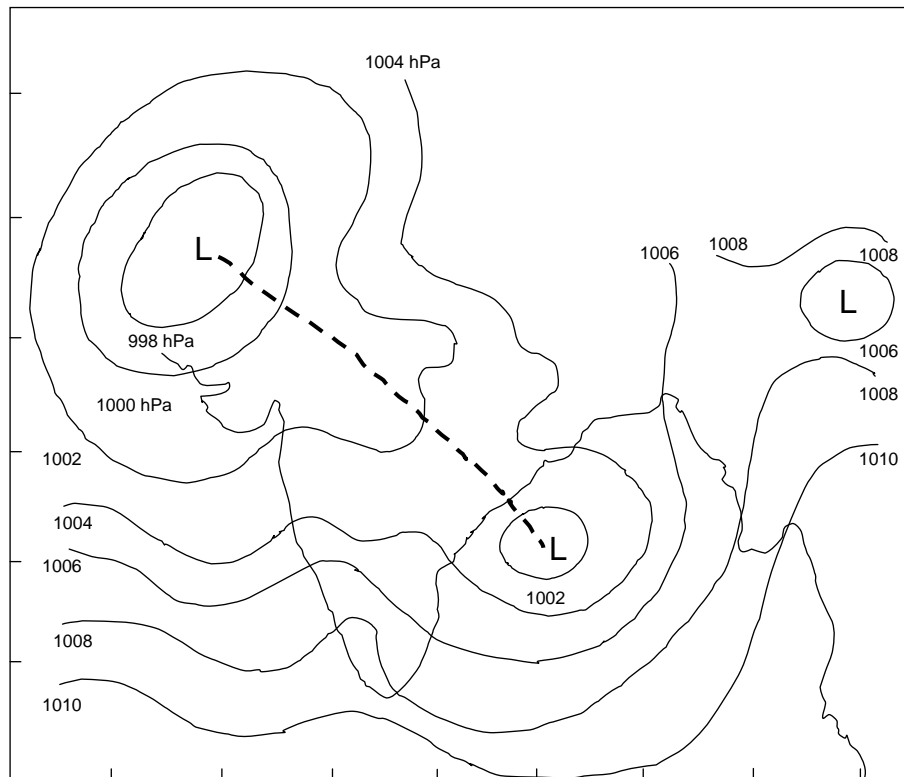


Fig. 1. Surface weather charts on 5 July 2003 at 0300 UTC

above 4 km. Their contribution is 47 (41) % for east (west) Rajasthan in which MTC is dominating feature in 35 (32) % cases for causing onset of summer monsoon. In addition MTC was also associated in some other cases on 8 occasions as shown in Table 2 superscripted by “m”.

Type-III Influence of western disturbances

In association with western disturbances (WD) moving across extreme north of the country in the lower troposphere, cyclonic vortices are sometimes formed over northwest India (Sengupta 1986). It has been concluded by number of studies that rainfall in northwest India including Rajasthan is not only influenced by tropical system approaching from the east but also by the trailing edge of the trough in the westerly in mid and upper troposphere. Both the systems even interact and causing rain (Rao, 1976). The frequencies of WDs are less during monsoon period as compared to the other seasons. It plays an important role in enhancing and sucking up of the Arabian Sea branch of monsoon and also Bay of Bengal current on some occasions over Rajasthan as subscript ‘w’ mentioned in Table 2 during the period of studies. During

the period of studies when there is lack of intense monsoon disturbance, only the WD contributes for onset of summer monsoon over Rajasthan. It contributes on 5(3) occasions for east (west) Rajasthan.

Type-IV Lopar in situ

On some situations low pressure area developed over Rajasthan *in situ* and causing onset there. On two occasions (in 1980 & 2000) such lopar developed for onset of southwest monsoon over west Rajasthan.

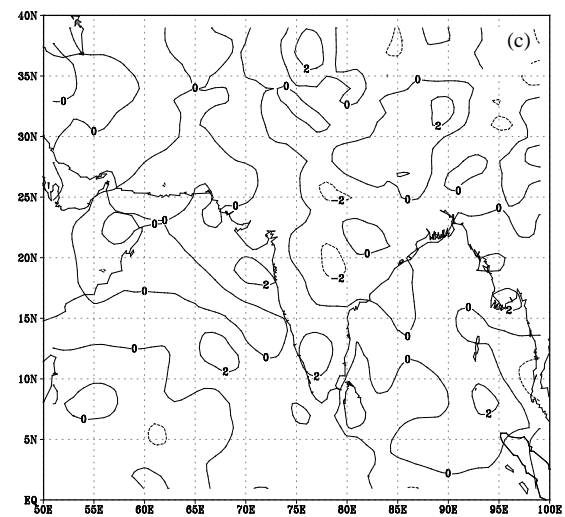
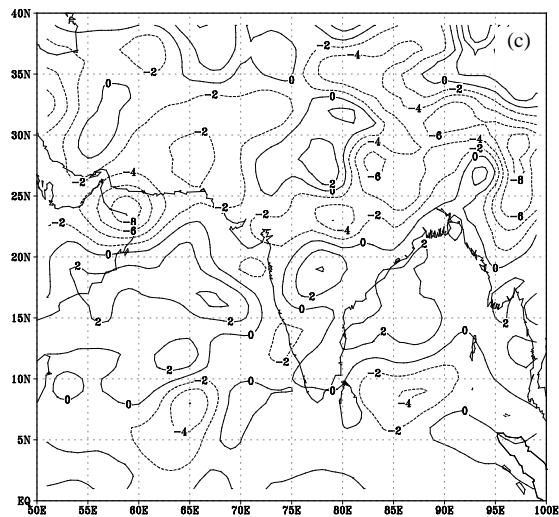
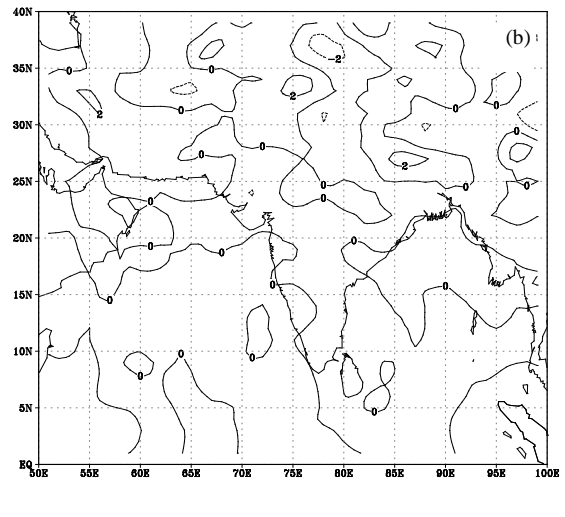
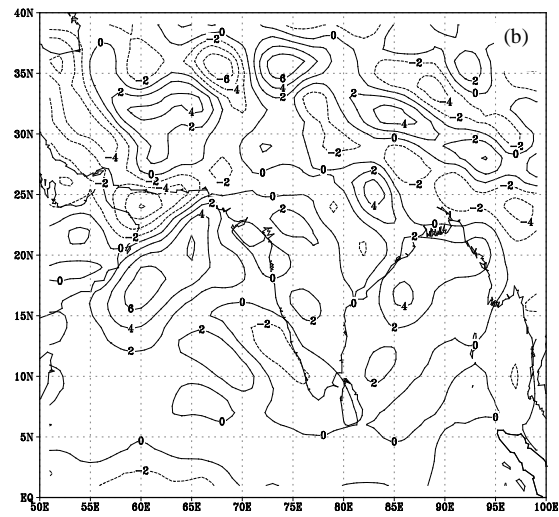
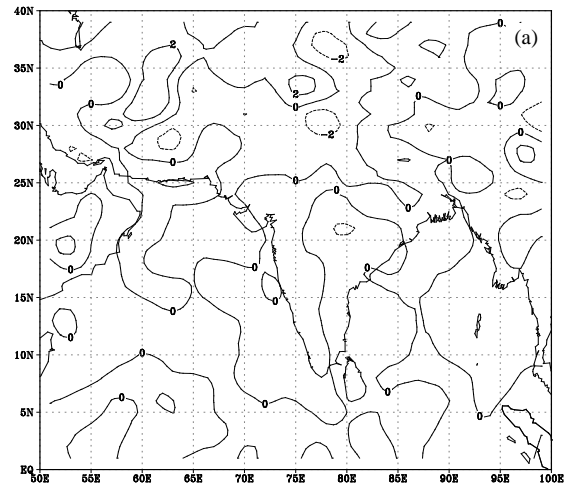
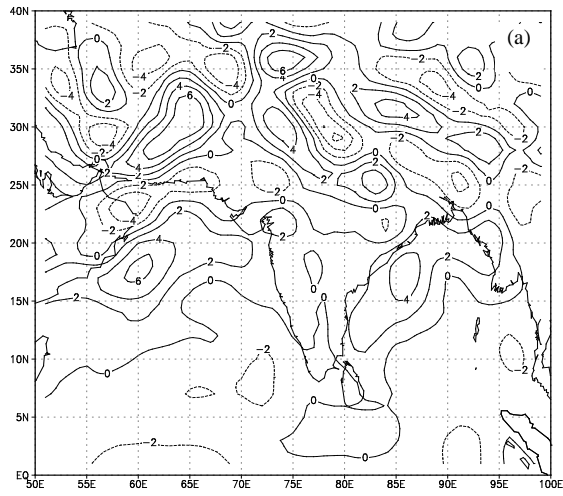
5. Case studies

In this section, typical cases of synoptic situations, which caused onset over Rajasthan, are briefly discussed.

5.1. *I case: 5th July 2003*

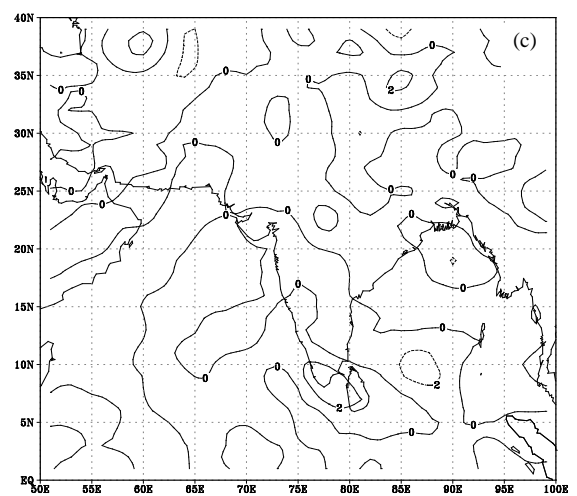
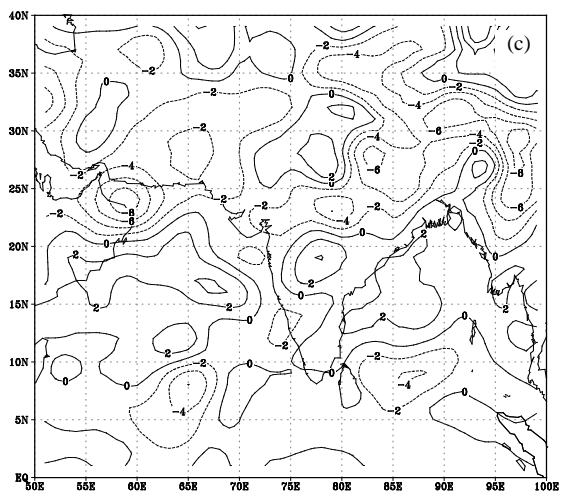
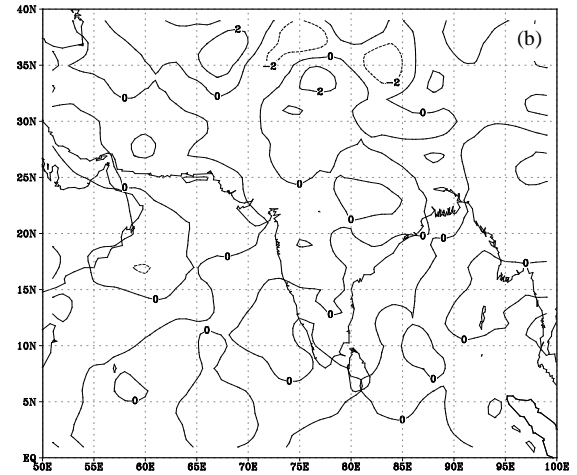
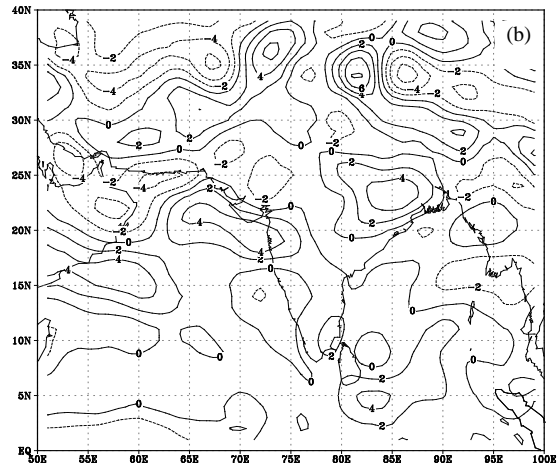
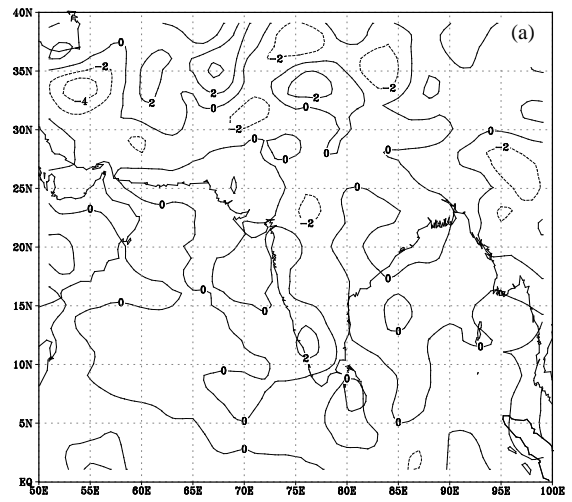
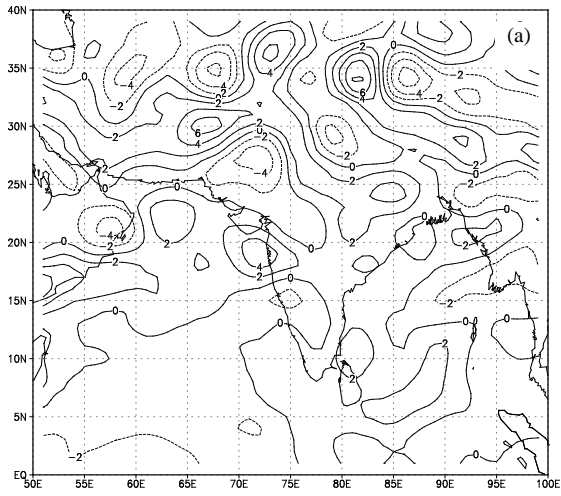
Onset over east (west) Rajasthan

A low pressure area formed over west central and adjoining northwest Bay off north Andhra - south - Orissa coast on 5th July 2003. the associated cyclonic circulation extended up to mid troposphere level (MTL). Another upper air cycir lay over northeastern Arabian Sea,



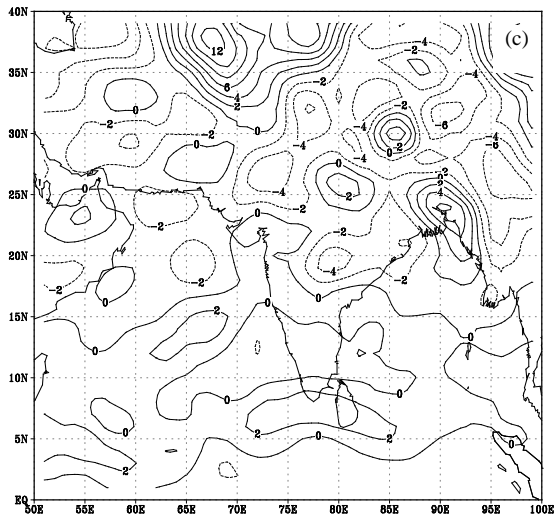
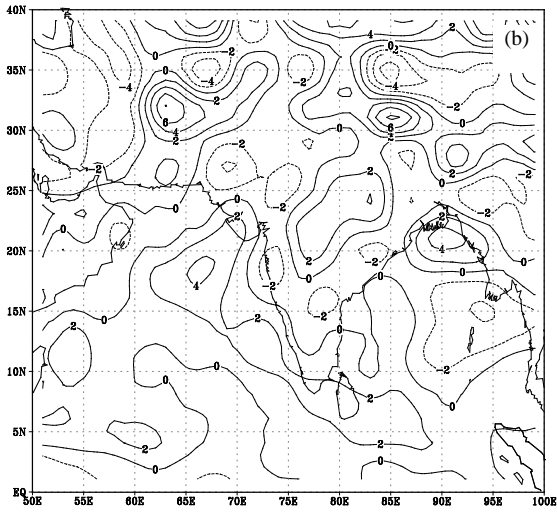
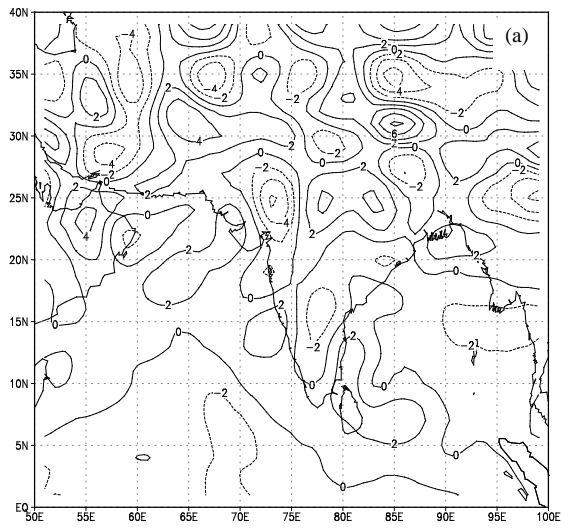
Figs. 2(a-c). Vorticity 0000 UTC/05 July 2003 (a) 850, (b) 700 & (c) 300 hPa

Figs. 3(a-c). Divergence 0000 UTC/05 July 2003 (a) 850, (b) 700 & (c) 300 hPa

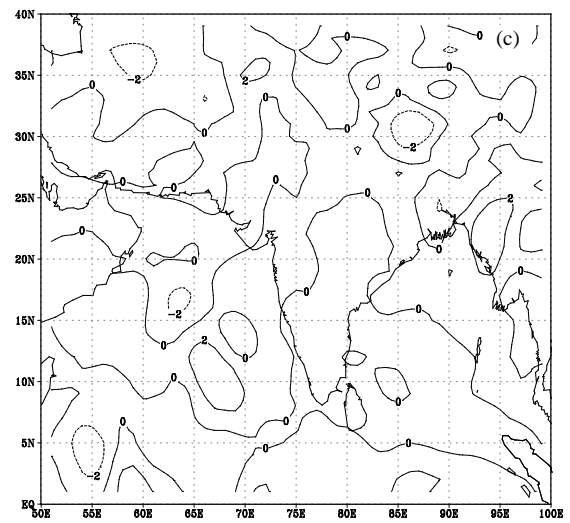
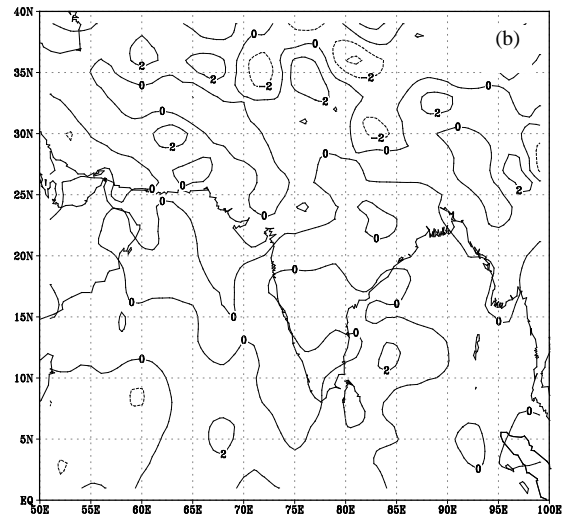
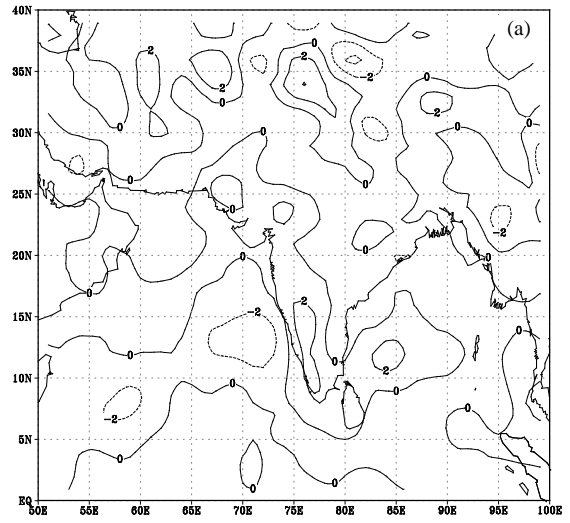


Figs. 4(a-c). Vorticity 0000 UTC/05 July 2004 (a) 850, (b) 700 & (c) 300 hPa

Figs. 5(a-c). Divergence 0000 UTC/05 July 2004 (a) 850, (b) 700 & (c) 300 hPa



Figs. 6(a-c). Vorticity 0000 UTC/18 July 2004 (a) 850, (b) 700 & (c) 300 hPa



Figs. 7(a-c). Divergence 0000 UTC/18 July 2004 (a) 850, (b) 700 & (c) 300 hPa

adjoining Gujarat and south Rajasthan during 3-6 July 2003 (MTC). The off shore trough at sea level running from Maharashtra coast to Kerala coast during the first week of July. Fig. 1 represents analysis of sea level chart at 0300 UTC dated 05 July 2003. The associated vorticity and divergence in upper air are presented in Figs. 2 & 3 and the associated cloudiness as seen in an INSAT (KALPANA-I) picture is shown in Fig. 8(a). Under the influence of above system, monsoon had been vigorous over east Rajasthan and active over west Rajasthan accompanied with onset of monsoon over east & west Rajasthan on 5 July 2003.

Chief amounts of rainfall (cm) as follows:

East Rajasthan : Mandalgarh 7, Pilani & Dholpur 6 each, Lachmangarh & Angai 5 each, Beawar, Raipur, Kishangarh, Amabad & Dungala 4 each, Kumalgarh, Baran, Milsagar, Sepua, Bayan & Kumapur 3 each, Ajmer, Pushker, Masuda, Manliyars, Jawaja, Bari, Shahpura, Kotkashim, Gangapur & Chittorgarh 2 each

West Rajasthan: Osiya, Churu, Ratangarh, Sujangarh & Rajgarh 3 each, Ora Tank 2

5.2. II case in 2004

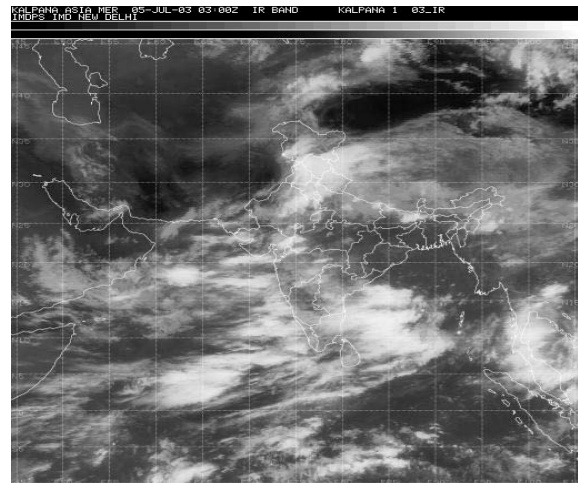
Onset over east Rajasthan on 5 July, 2004

A lobar formed over northwest Bay and adjoining land area on 3 July, 2004 and moved & lay over Chhatisgarh with associated cycir between 1.5 km & 4.5 km a.s.l. on 5 July, 2004. A cycir lay over northeast Arabian sea and adjoining land area between 2.1-4.5 km a.s.l. Another cycir was seen over northwest-Rajasthan & neighbourhood extending upto 2.1 km a.s.l. The axis of monsoon trough on sea level chart was passed through: Firozpur-Hisar-Orai-Jamshedpur & thence southeastwards to Bay. The associated chief amounts of rainfall (cm) as follows:

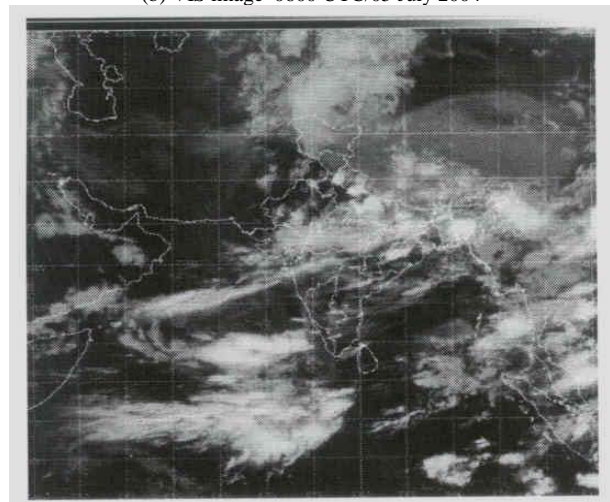
East Rajasthan : Jhalawar 8, Chiklawas 5, Degana & Jamwa Ramgar 4 each, Jayal, Merta & Sri Madhopur 3 each, Shahpura, Bhawanigarh, Beawar, Khivensar, Didwana, Urmilsagar, Ramganj Mandi & Gogunda 2 each

West Rajasthan: Boli & Rohit 3 each, Jodhpur & Bihara 2 each

(a) IR image 0300 UTC/05 July 2003



(b) VIS image 0600 UTC/05 July 2004



(c) IR image 2100 UTC/17 July 2004

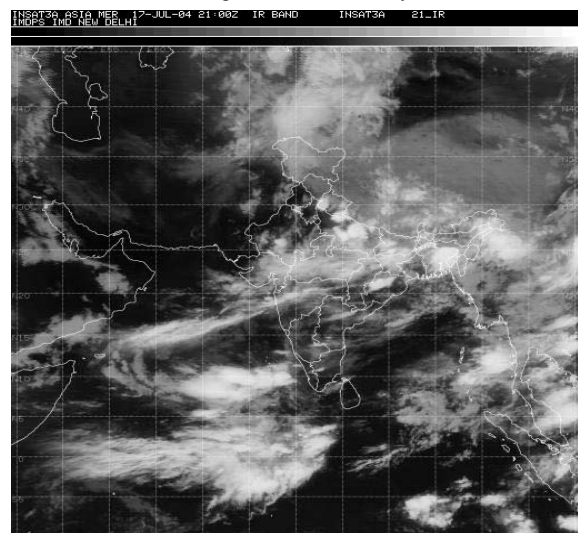


Fig. 8. KALPANA-I cloud imageries

Onset over west Rajasthan on 18 July, 2004

An upper air cycir was seen over north Rajasthan & neighbourhood upto 2.1 km a.s.l. due to passage of a WD. A low was at 500 hPa over north-Rajasthan. The cycir lay over northeast Arabian Sea and neighbourhood between 2.1 & 4.5 km a.s.l. On sea level chart the axis of seasonal trough was passed through Firozpur-Dehradun-to foot hills. Under the influence of these systems monsoon was active over east Rajasthan and monsoon onset over west Rajasthan. Vorticity and divergence in upper air are presented in Figs. 4, 5, 6 & 7 and the associated cloudiness as seen in an INSAT (KALPANA-I) picture is shown in Figs. 8 (b&c).

Chief amounts of rainfall (cm) as follows:

East Rajasthan : Kapasan 13, Bhansroad Garh 12, Railmagra 9, Meja Dam, Bijolia & Bhadesar 7 each, Dungla & Khairi Dam 6 each, Merata, Bhim, Choti Sadri, Toda Raisingh, Baseri, Kandar & Rawatbhata 5 each, Matri Kundla, Jawaja, Tatgarh, Jait Pura, Dholpur, Mundawan, Mungapur, Badi Sadri, Begu, Gangrar & Udaipur city 4 each, Talabpura, Dabok, Devgarh, Manohar Thana, Bhilwara, Chandsen, Nagaur, Vijayanagar, Bhinay & Ajan Bandh 3 each, Roopwas, Alab Shahi, Beawar, Maleraina Dungar, Pratapgarh, Deval, Rajsamand, Nathdwara & Ketwara 2 each

West Rajasthan : Marwari Junction 8, Bilara 7, Raipur 6, Sejat 5, Jatarain & Desuri 4 each, Loharia 2

6. Conclusions

The present study over the Rajasthan State based on the data for a period 1971-2004 suggested that :

(i) The low pressure systems originating over Arabian sea a prominent feature specially formation of MTC in association with WD activates Arabian sea current over Rajasthan causing onset of monsoon there.

(ii) The LPS formed over Bay of Bengal are the second main synoptic situation responsible for onset of summer monsoon over Rajasthan. These LPS from Bay of Bengal generally reached to the Rajasthan region or neighbourhood region in 4-5 days.

(iii) No depression was developed over Bay after 1984 except in 1999, which could bring onset of monsoon over Rajasthan.

(iv) No lopar over Bay got success to reach Rajasthan region for incursion of onset after 1989 (1994) for east (west) Rajasthan.

(v) In preceding 10 years development of MTC in association with WD has been the prominent synoptic features to set in monsoon over Rajasthan. Therefore development of MTC indicates a good signature for predicting onset of monsoon for a synoptician.

Acknowledgements

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