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QPF Model for lower Yamuna catchment, synoptic analogue method

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सार – इस शोध पत्र में दक्षिणी मानसून ऋतु के दौरान ग्यारह वर्षों के आँकडों (1998–2008) के आधार पर यमुना जलग्रहण के निचले क्षेत्रों (एल. वाई. सी.) के लिए परिमाणात्मक वर्षण पूर्वानुमान (क्य. पी. एफ.) जारी करने के लिए एक सिनॉप्टिक अनुरूप निदर्श तैयार किया गया है। वर्ष 2009 के दक्षिणी पश्चिमी मानूसन ऋतु के दौरान सदृश्य सिनॉप्टिक स्थिति के लिए प्राप्त हुए औसत क्षेत्रीय वर्षा (ए. ए. पी.) के साथ इस निदर्श से प्राप्त हुए परिणामों की जाँच की गई है। इस निदर्श का निष्पादन प्रतिशत 86% तक सही देखा गया है और प्रचंड घटनाओं में यह हेडीक स्क्लि स्कोर (एच. एस. एस.) मान 0.9 के साथ 100% सही देखा गया है। दक्षिणी पश्चिमी मानसून 2009 के तथ्यों से यह पता चला है कि केन्द्रीय जल आयोग को बाढ़ पूर्वानुमानों की सुविधा देने के लिए सिनॉप्टिक अनुरूप निदर्श, 24 घंटे पहले परिणामात्मक वर्षण पूर्वानुमान (क्यू. पी. एफ.) सटीकता और सही कुशलता के साथ दे सकता है।

ABSTRACT. The paper formulates a synoptic analogue model for issuing Quantitative Precipitation Forecast (QPF) for Lower Yamuna Catchment (LYC) based upon eleven years data (1998-2008) during southwest monsoon season. The results so derived were verified with realized Average Areal Precipitation (AAP) for the corresponding synoptic situation during 2009 southwest monsoon season. The performance of the model was observed Percentage Correct (PC) up to 86 % and for extreme events showed 100% correct with Heidke Skill Score (HSS) value 0.9. The experience during south west monsoon 2009 has shown that Synoptic analogue model can produce 24 hours advance QPF with accuracy and greater skill to facilitate the flood forecasters of Central Water Commission.

Key words – AAP, QPF, Synoptic analogue model, Rain storms, Yamuna, Catchment, Flood, Ranges.

1. Introduction

Flood Forecasters cannot rely only upon observed precipitate in the field of hydrological prediction for medium-sized catchment with short response time to rainfall events. Predicted rainfall is an essential input for hydrological models that produces river stage forecasts to increase the lead time up to a minimum critical value required for the activation of civil plan. Now-a-days rainfall forecasting is approached through Numerical Weather Prediction (NWP) models, even though only limited area models (LAMs) have a spatial and temporal resolution that may be adequate for hydrological applications. However, the capability of such models to forecast correctly local and intense precipitation is still limited, even at short time-range, up to 48 h, primarily due to atmospheric instabilities which causes observation-analysis errors, tending to affect more adversely the smaller scales typical of medium-sized watersheds. Also for the Indian monsoon region, MM5 Model shows better skill along Western Ghats and over the North Bay of Bengal, but fails over the domain of monsoon trough for predicting rainfall whereas LAM shows better skill over the domain of monsoon trough and performs poor along Western Ghats and over the North Bay of Bengal (Roy Bhowmik and Durai, 2008). As a consequence, deterministic meteorological models (NWP), even the high resolution ones, cannot produce reliable quantitative precipitation forecasts to be used directly for flood forecasting purposes. Therefore it demands that the problem of QPF should be tackled relying upon alternative methodologies based on a statistical probabilistic approach. Several studies to develop QPF models have been made to improve weather forecast accuracy (Rodriguez-Iturbe *et al*., 1987; Foufoula-Georgiou and Krajewski, 1995; Todini, 1999; Marsigli *et al*., 2001; Schaake, 2004). Obled *et al*. 2002 describes an approach which can be treated as an adaptation of deterministic meteorological model output. This method was calibrated over about 50 catchments located in France, Italy and Spain, using a meteorological and hydrological archive for the period 1953 to 1996.

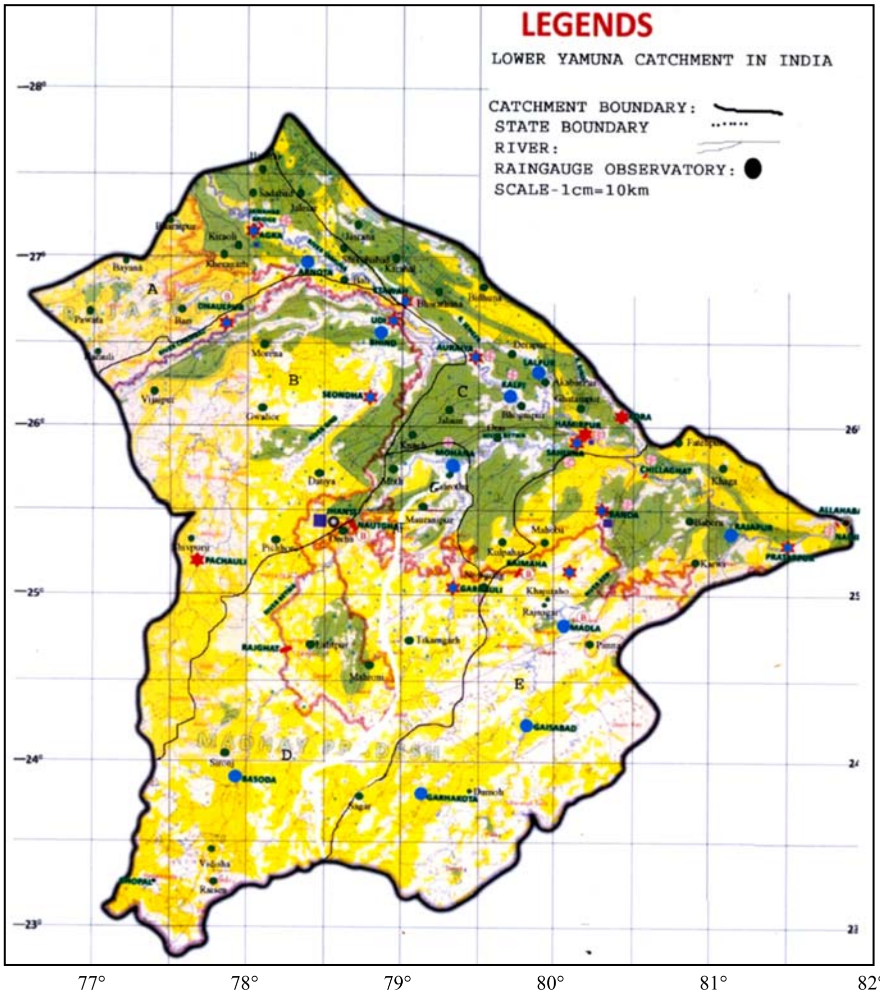


Fig. 1(a). Basin map of Lower Yamuna catchment

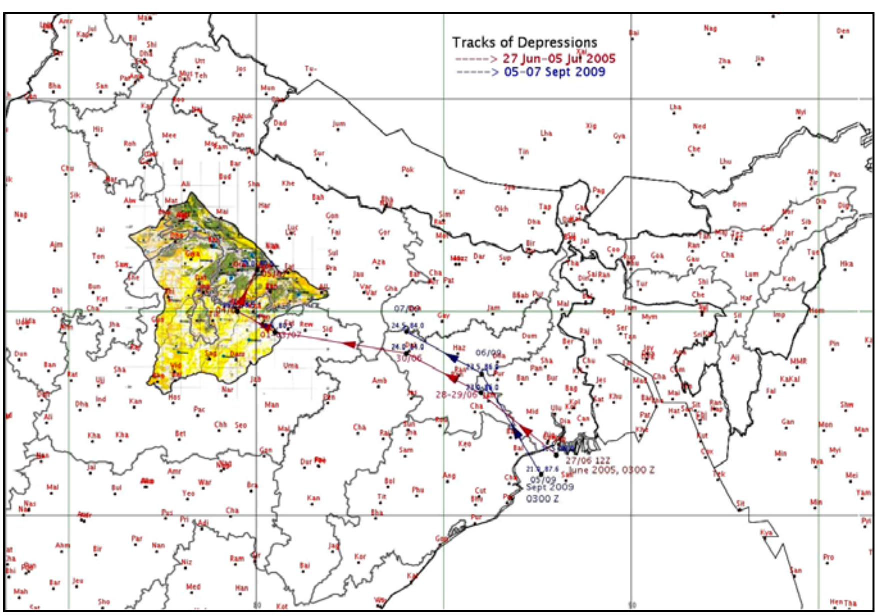


Fig. 1(b). Tracks of Depressions during the period 27 June – 05 July 2005 and 05-07 September 2009

Comparisons carried out over a validation sample (1995-96) with three poor-man methods prove the worthiness of this approach, in a perfect prognosis context. Krzysztofowicz *et al*. 1993 formulated a methodology to aid flood forecasters in preparing probabilistic quantitative precipitation forecasts (QPFs) for river basins. The methodology, implemented as a human-computer system, has been tested operationally on two river basins by the Weather Service Forecast Office in Pittsburgh, Pennsylvania, since August 1990.

In the present study, a synoptic analogue approach to predict QPF is proposed. This technique is based upon the concept of analogy applied in meteorology and exploits the reliable representation of large scale hydrodynamic variables, like geo-potential fields, provided by NWP models to derive precipitation forecast indirectly. The analogue method has already been employed in several studies and has been demonstrated as a valid alternative way to issue precipitation forecast (Radinovic, 1975; Vislocky and Young, 1989; Roebber and Bosart, 1998; Obled *et al*., 2002). It is employing the philosophy that weather behaves in such a way that the present initial conditions, if found to be similar to a past situation, will evolve in a similar fashion and it is easy to find good analogues over a small area, even if the data-set available for the analogue research is short (Roebber and Bosart, 1998). However, the prediction of QPF provided by analogues can be considered not only competitive but rather complementary with the deterministic one supplied by NWP models (Djerboua and Obled, 2002). Studies in past decades evidenced that weather patterns over certain areas and over the entire Northern Hemisphere tend to repeat themselves from time to time (Lorenz, 1969). In addition, the synoptic meteorology is the backbone to predict QPF. Synoptic Analogue Technique is easily accessible in view of operational forecasting method. Abbi *et al*. (1979) studied the movement of cyclonic storms/depression/monsoon trough for a period 1960-76 with respect to Bhagirathi catchment and prepared analogue maps. Similar concerted efforts have been made by others to issue QPF by synoptic analogue method *viz*., Lal *et al*. (1983), Ray and Saha (1998), Ray and Patel (2000), Ram and Kaur (2004) over river catchments of Gomti, Sabarmati, Narmada and Upper Yamuna river respectively. In a similar manner an attempt has been made to identify the different synoptic systems and their location which are responsible for Average Areal Precipitation (AAP) in the ranges 11-25, 26-50, 51-100 and > 100 mm during the southwest monsoon season over the Lower Yamuna Catchment (LYC) for the period 1998 – 2008 and then formulates a synoptic analogue model accordingly. It is especially needed for Flood Forecasting officials of Central Water Commission and civil protection authorities.

LYC lies on the southern side of the river Yamuna. Its catchment area is comprised of land in southwest (SW) part of Uttar Pradesh (U.P.), parts of Rajasthan and northwest (NW) part of Madhya Pradesh (M.P.). (Central Water Commission Appraisal report' 2008 Lower Yamuna river division). Yamuna rises in the glacial region of Yamunotri in Tehri Garhwal at an altitude of 6320m amsl and is enjoyed by a number of tributaries. The river flows almost in southerly direction up to Mathura and thence in southeasterly direction to reach Agra channel from where LYC basin [Fig. 1(a)] starts and then in almost easterly direction to Etawah, Auraiya, Hamirpur, Naini (Allahabad) to join the Ganga. The Yamuna between Agra to Allahabad is enjoyed by its principal tributaries Chambal, Sind, Betwa and Ken. LYC area up to Naini is about 182613 sq km, while total catchment area from Yamunotri to Naini is 366223 sq km. including Chambal catchment. The total length of Yamuna is 1376 km, while in LYC region it is 733 km. River Chambal is the largest tributary of Yamuna which originates in the Vindhya ranges near Mhow in Indore district of M.P. at an elevation of 354 m above m.s.l. having its drainage area in Madhya Pradesh and Rajasthan, joining Yamuna 20 km upstream of Auraiya on the right bank. It's total catchment area is 139468 sq km, out of it about 3218 sq km covers in LYC. The Betwa river rises in the Bhopal district at an elevation of 475 m above m.s.l. flowing generally in northeast direction before it enters Lalitpur district of UP. The Betwa meets Yamuna at Hamirpur, while Dhasan tributary meets Betwa near Mohana. The river length is 483 km with drainage area about 46580 sq km. Floods due to spilling of water over plains around its confluence with Yamuna threatening the town of Hamirpur is problematic during high stages of the river. The Ken river has it's origin in the North-Western Slopes of Kaimur hills in Satna district of Madhya Pradesh flowing generally in south-north direction and joins Yamuna near Chillaghat after traveling a distance of about 360 km with drainage area of 28,224 sq km. Banda is the most important town on its right bank. The floods downstream of Banda are caused due to synchronization of medium to high floods in Yamuna with flood in Ken.

2. Adaptation and application of QPF prediction

The steadily increasing of the damages due to flood and particularly flash flood events, in terms of both number of casualties and economic costs, has led to heighten interest in flood forecasting systems. A crucial component of these systems is the flood forecasting modelling in which predicted QPF rainfall is an essential and important effective input. The developing of the synoptic analogue method to predict QPF in time has evidenced it's advantages. It can be simply implemented and is capable of quickly generating objective forecasts;

TABLE 1

Frequency of occurrence of AAP more than 10 mm for various synoptic situations

	Sub Catchment Area - A					Sub Catchment Area - B					Sub Catchment Area – C					Sub Catchment Area - D					Sub Catchment Area - E					
System	11-25	26-50	51-100	> 100	Total	11-25	26-50	51-100	> 100	Total	11-25	26-50	51-100	> 100	Total	11-25	26-50	51-100	> 100	Total	11-25	26-50	51-100	> 100	Total	Grand Total
													Year : 1998-2008													
S11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S12	2	0	0	0	2	4	0	1	0	5	1	1	0	0	2	3	3	1	0	7	4	2	1	0	7	23
S13	1	1	0	0	2	3	1	0	0	4	1	0	0	0	1	1	4	1	0	6	3	1	0	0	4	17
S14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	*3*	*1*	*0*	*0*	*4*	*7*	*1*	*1*	*0*	*9*	*2*	*1*	*0*	*0*	*3*	*4*	*7*	*2*	*0*	*13*	*7*	*3*	*1*	*0*	*11*	*40*
S21	9	1	0	0	10	5	2	0	0	7	7	2	2	0	11	7	5	2	0	14	11	2	0	0	13	55
S22	2	0	0	0	2	7	4	0	0	11	9	1	1	0	11	9	4	1	0	14	12	3	1	0	16	54
S23	5	0	0	0	5	8	0	1	0	9	4	2	0	0	6	11	9	1	0	21	6	1	1	0	8	49
S24	11	7	0	0	18	9	3	1	0	13	6	2	1	0	9	8	3	1	1	13	8	2	0	0	10	63
Total	*27*	*8*	*0*	*0*	*35*	*29*	*9*	*2*	*0*	*40*	*26*	*7*	*4*	*0*	*37*	*35*	*21*	*5*	*1*	*62*	*37*	*8*	*2*	*0*	*47*	*221*
S31	16	4	2	0	22	15	7	1	0	23	18	8	2	0	28	20	7	1	0	28	29	9	1	0	39	140
S32	6	2	0	0	8	6	1	0	0	7	10	0	0	0	10	11	2	0	0	13	12	2	0	0	14	52
S33	6	3	0	0	9	8	1	1	0	10	7	3	0	0	10	5	5	0	0	10	9	0	0	0	9	48
S34	21	6	0	0	27	25	6	2	0	33	19	7	0	0	26	26	6	0	0	32	32	8	1	0	41	159
Total	*49*	*15*	*2*	*0*	*66*	*54*	*15*	*4*	*0*	*73*	*54*	*18*	*2*	*0*	*74*	*62*	*20*	*1*	*0*	*83*	*82*	*19*	*2*	*0*	*103*	*399*
S41	5	3	0	0	8	6	3	0	0	9	5	2	0	0	7	9	2	0	0	11	7	2	0	0	9	44
S42	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1	2	0	0	0	2	2	0	0	0	2	6
S43	1	0	0	0	1	3	0	0	0	3	1	0	0	0	1	3	0	0	0	3	0	0	0	0	0	8
S44	9	2	2	0	13	4	2	0	0	6	2	2	0	0	4	5	2	0	0	7	5	1	0	0	6	36
Total	*15*	*5*	*2*	*0*	*22*	*14*	*5*	*0*	*0*	*19*	*8*	*4*	*1*	*0*	*13*	*19*	*4*	*0*	*0*	*23*	*14*	*3*	*0*	*0*	*17*	*94*
G.Total	**94**	**29**	**4**	**0**	**127**	**104**	**30**	**7**	**0**	**141**	**90**	**30**	**7**	**0**	**127**	**120**	**52**	**8**	**1**	**181**	**140**	**33**	**5**	**0**	**178**	**754**

furthermore it does not rely upon complex and subtle reasoning inherent in physical/statistical methods (Radinovic, 1975; Bergen and Harnack, 1982; Toth, 1989), yielding a real solution to a difficult problem and not introducing any simplification over the physics of the atmosphere (Van den Dool, 1989). So it is suitable and fit to use in hydrological model for flood forecast purposes etc. Adaptation and application of QPF in river forecasts allows for longer lead time and increased forecast reliability and usefulness. QPFs and the products generated using QPFs are important in flood and non-flood conditions and are used by flood control agencies, water management, districts and emergency management agencies to reduce the loss in terms of life and property and breakdown of the infrastructures (Opitz *et al.* 1995, Krzystofowicz *et al.* 1993). In particular, forecasting flash floods and rapidly evolving floods which develop within 24 hours should be improved by the incorporation of QPF. Not only does incorporation of QPF enable more reliable river forecasts to be issued, it also reduces the need for forecast revisions during a precipitation event. The goal of QPF is to facilitate the timely dissemination of potential life- saving information to emergency management agencies and the public. The ability to extend the forecast period resulting from QPF allows for better, more timely responses to river forecasts.

3. Method and data

In order to apply synoptic analogue technique over LYC, various synoptic situations during southwest monsoon season for 11 year period (1998-2008) based upon 0000 UTC/1200 UTC upper air and 0300/1200 UTC surface charts in relation to different ranges of rainfall have been categorized using Regional Daily Weather Reports and IDWRs. The rains storms less than 11 mm are considered to have negligible effect in changing the river gauges, so the rainstorms ranges 11-25, 26-50, 51-100 mm and more than 100 mm have been considered for matching with different synoptic systems in the present

TABLE 2

Verification of synoptic analogue of Q.P.F. for Lower Yamuna catchment for 2009 SW-monsoon season sub-catchment wise

S. No.	Synoptic situation code	Number of cases realized	QPF Range (mm) as per the analogue	Realized mean AAP (mm)	Number of cases when QPF is	
					Correct	Out by one stage (*Under/ Over estimate)
	Sub-catchment A					
1.	S12	01	11-25	18	01	00
2.	S22	01	11-25	15	01	00
3.	S23	01	11-25	11	01	00
4.	S24	01	26-50	29	01	00
5.	S31	02	11-25	15	02	00
6.	S32	02	11-25	13	02	00
7.	S33	02	26-50	25	01	01
8.	S34	02	11-25	24	01	01*
9.	S44	02	11-25	13	02	00
	Sub-catchment B					
10.	S12	01	11-25	13	01	00
11.	S22	03	26-50	23	01	02
12.	S23	01	26-50	16	00	01
13.	S24	01	11-25	12	01	00
14.	S31	02	26-50	27	02	00
15.	S32	02	11-25	21	02	00
16.	S33	01	11-25	26	01	00
17.	S34	04	26-50	28	02	02
18.	S41	01	11-25	11	01	00
19.	S44	01	11-25	17	01	00
	Sub-catchment C					
20.	S12	01	11-25	11	01	00
21.	S22	01	26-50	26	01	00
22.	S24	01	26-50	32	01	00
23.	S31	02	26-50	49	02	00
24.	S32	02	11-25	14	02	00
25.	S33	03	11-25	15	03	00
26.	S34	03	11-25	18	02	01*
27.	S41	01	11-25	15	01	00
	Sub-catchment D					
28.	S12	01	26-50	38	01	00
29.	S22	02	11-25	18	02	00
30.	S23	01	26-50	14	00	01
31.	S31	02	26-50	40	02	00
32.	S32	02	11-25	18	02	00
33.	S33	03	11-25	19	02	01*
34.	S34	01	11-25	21	01	00
35.	S41	01	11-25	28	01	00
	Sub-catchment E					
36.	S12	01	11-25	11	01	00
37.	S22	02	11-25	13	02	00
38.	S23	01	26-50	26	01	00
39.	S24	01	26-50	43	01	00
40.	S31	02	51-100	62	02	00
41.	S32	01	26-50	26	01	00
42.	S33	02	11-25	14	02	00
43.	S34	01	26-50	26	01	00
44.	S41	01	26.50	32	01	00
45.	S44	01	11-25	15	01	00
Total		71			61(86%)	10(14%)

Grand Total = 71 , (S12 = 5, S22 = 9, S23 = 4, S24 = 4, S31 = 10, S32 = 9, S33 = 11, S34 = 11, S41 = 4, S44 = 4)

TABLE 3

QPF Model for Lower Yamuna catchment

Sub catchment	Zone	Met sub-division	S1	S2	S3	S4
A	1	E – UP	11 – 25	Nil	11 – 25	26 – 50
	2	SE – UP & Adj. MP	11 – 25	11 – 25	11 – 25	Nil
	3	NW – MP & Adj. UP	11 – 25	11 – 25	26 – 50	11 – 25
	4	NW– UP & Adj E-Raj	Nil	26 – 50	11 - 25	11 – 25
B	1	E – UP	Nil	11 – 25	26 – 50	11 – 25
	2	SE – UP & Adj. MP	11 – 25	26 – 50	11 – 25	11 – 25
	3	NW – MP & Adj. UP	11 – 25	11 – 25	11 – 25	11 – 25
	4	NW–UP & Adj E-Raj	Nil	11 - 25	26 - 50	11 – 25
C	1	E – UP	Nil	26 – 50	26 – 50	11 – 25
	2	SE – UP & Adj. MP	11 – 25	26 – 50	11 – 25	> 50
	3	NW – MP &Adj. UP	11 – 25	11 – 25	11 – 25	11 – 25
	4	NW– UP& Adj E-Raj	Nil	26 – 50	11 – 25	11 – 25
D	1	E – UP	Nil	26 – 50	26 – 50	26 – 50
	2	SE-UP & Adj. MP	26 – 50	11 – 25	11 – 25	11 – 25
	3	NW – MP & Adj. UP	26 – 50	26 – 50	11 – 25	11 – 25
	4	NW–UP& Adj E- Raj	Nil	26 – 50	11 – 25	11 – 25
E	1	E – UP	Nil	26 – 50	51-100	26 – 50
	2	SE – UP & Adj. MP	11 – 25	11 – 25	26 – 50	11 – 25
	3	NW – MP & Adj. UP	11 – 25	26 – 50	11 – 25	Nil
	4	NW– UP& Adj. E-Raj	Nil	26 – 50	26 – 50	11 - 25

E – UP : East Uttar Pradesh
SE–UP & Adj. MP: Southeast Uttar Pradesh and adj. Madhya Pradesh
NW – MP &Adj. UP: Northwest Madhya Pradesh and adj. Uttar Pradesh
NW– UP& Adj .E-Raj : Northwest Uttar Pradesh and adj. East Rajasthan

study. Rainfall data have been collected and daily AAP of 90 stations distributed in LYC region has been computed using arithmetic mean method.

Sub-divisions under LYC Area (Zones)

(*i*) East U.P.

(*ii*) Southeast U.P. and adjoining North east M.P.

(*iii*) Northwest M.P. and adjoining southwest U.P.

(*iv*) Northwest U.P. & adjoining East Rajasthan.

Synoptic system responsible for considerable amount of rainfall during southwest monsoon season are follows:

(*i*) S1: Cyclonic storm/ Depression

(*ii*) S2 :Well marked low Pressure area (LOPAR)

(*iii*) S3: Upper air cyclonic circulation (CYCIR)

(*iv*) S4 : Monsoon trough

According to above classification the system S23 stands for LOPAR over Northwest MP. & adjoining southwest U.P. and so on so forth.

4. Results and discussion

The CWC Agra has divided the LYC region in nine sub-catchment areas, for which QPF is required. So these sub-catchment again reconstructed for convenience as A for 1, B for 2, C for 3, 4 & 7, D for 5 & 6 and E for 8 & 9 sub-catchment. The total 754 rainstorms associated with different types of synoptic situations are shown sub-catchmentwise A, B, C, D & E in Table 1 which depicts their frequency of occurrence of AAP more than 10 mm. The meteorological sub-divisions of East U.P., Southeast U.P. and adjoining North east M.P ., Northwest M.P. and adjoining southwest U.P., Northwest U.P. & adjoining East Rajasthan, the four zones in LYC region are considered very important in causing rain over the basin.

(*i*) Out of 754 occasions of more than 10mm rainfall about 53% (highest frequency) occurred due to the synoptic system upper air cyclonic circulation (Cycir) *i.e.*, (S3).

(*ii*) The next important synoptic system was observed Lopar (S2) have accounted for 29%.

(*iii*) The Monsoon trough (S4) accounted for 13% rainfall contribution.

TABLE 4

Results of the verification of Q. P. F. using Synoptic Analogue Method during SW-Monsoon 2009 applying 2 × 2 contingency table

Deterministic Forecast	
Type of Skill	Skill score
Probability of Detection (POD)	0.8
False Alarm Rate (FAR)	0.2
Missing Rate (MR)	0.2
Correct Non-occurrence (C-NON)	0.9
Critical Success Index (CSI)	0.7
Biased for Occurrence (BIAS)	1.03
Percentage Correct (PC)	85.7
Heidke Skill Score (HSS)	0.9

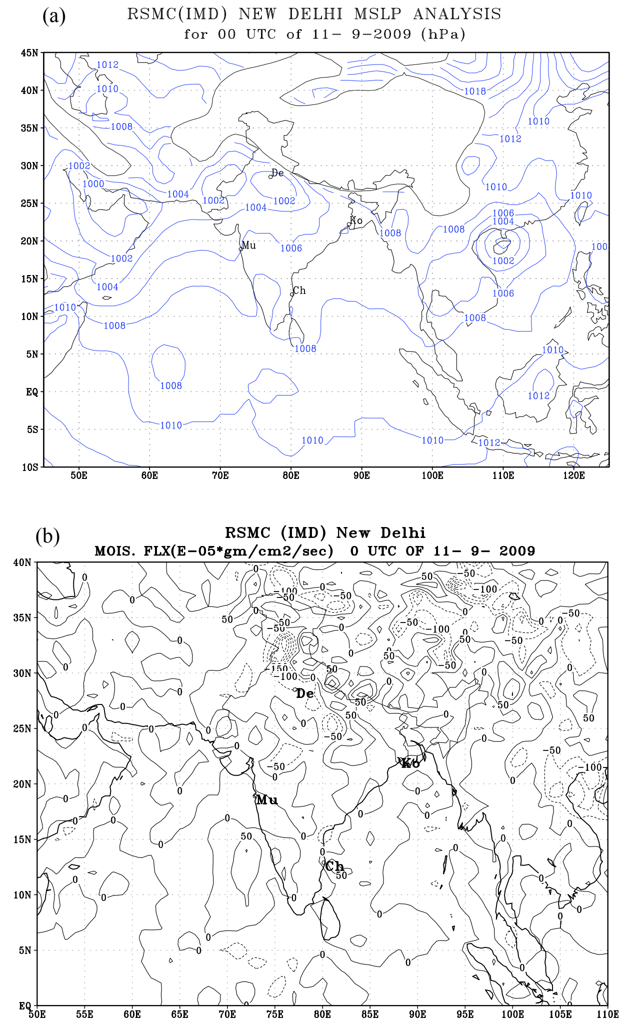
(*iv*) The Cyclonic storms/depression (S1) produced rainfall >10mm for 5% of the occasions.

(*v*) Out of 548 occasions in the range 11-25 mm the contribution of the synoptic systems S1, S2, S3 & S4 accounted for 4%, 28%, 55% & 13% respectively while in the category 26-50 mm, out of 174 occasions their contribution was found to be 7%, 31%, 50% & 12% respectively.

(*vi*) Out of 31 cases in the ranges 51-100 mm the systems S1, S2, S3 and S4 accounted for 13%, 42%, 36% and 9% respectively while in range > 100 mm, only one occasion was observed.

(*vii*) The frequency of depression is observed very low.

(*viii*) On the basis of the above statistics, Synoptic analogue model was developed as shown in Table 3 sub-catchmentwise. This model was applied to test the 71 rainstorms of different categories of southwest monsoon season of 2009 over LYC and the results are depicted in Table 2 sub-catchmentwise. At S.N. 1, (Table 2) S12 (occurred on 22 July, 2009, not shown in Table 2) lay over A sub-catchment yielded rainfall 18mm, as per Table 3, in the row of sub-catchment A under S1 column for zone 2 (Southeast U.P. and adjoining North east M.P) the corresponding QPF value is shown in the range 11-25, which is correct forecast value as shown in Table 2. Similarly when system S22 & S23 (at S.N. 2 & 3, Table 2) occurred over sub-catchment A, the corresponding QPF value in Table 3 in their respective zones 2 & 3 are in the range 11-25 mm which are also correct forecast as shown in Table 2. In similar fashion, the analogue as per Table 3 was applied to the other rainstorms shown in Table 2. Thus out of 71 total cases, QPF has been found correct with the AAP on 61 cases (86%), out by one stage on 10 cases (14%), it is due to

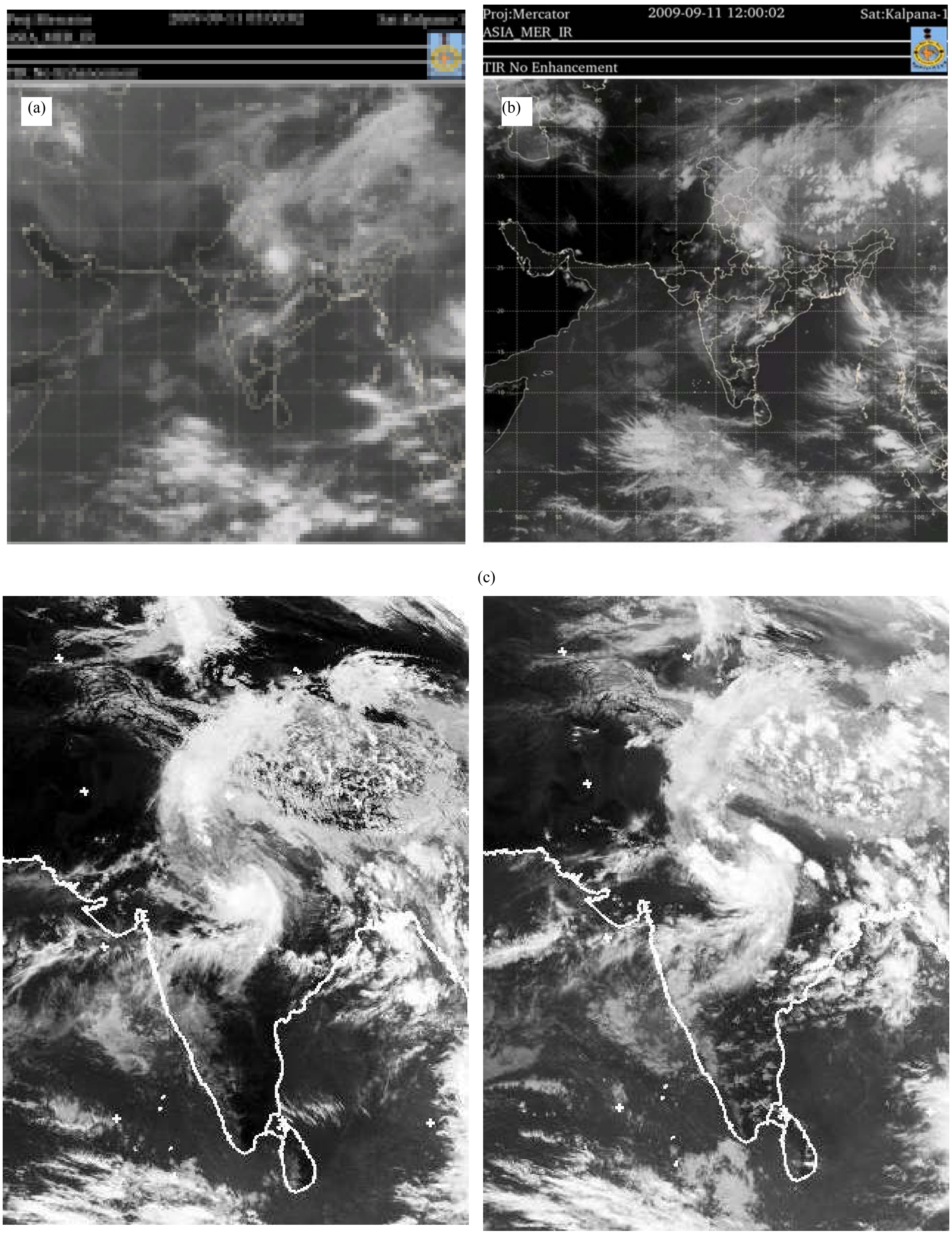


Figs. 2(a&b). (a) MSLP analysis for 0000 UTC of 11th September 2009 and (b) Moisture flux

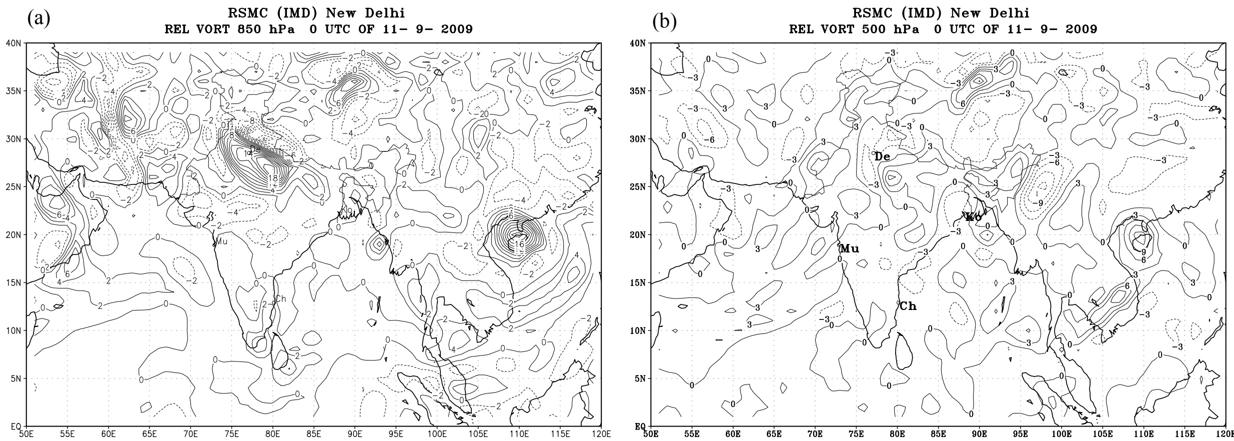
variation in the intensity of the system especially upper air cycir (S3) & Lopar (S2) systems over the basin. Also for extreme rainfall events (intense rainfall) the QPF model is found 100% correct. In Table 2 at S. No. 40, two such cases were observed in sub-catchment E with mean rainfall 62 mm & in the range 51-100 mm on 15th and 16th August 2009 due to the system S31. The intense rainfall ≥ 5cm are as follows in this area.

15 Aug 2009 : Rainfall observed (cm) : Kaimah:12, Chillaghat: 9, Karwi: 9, Baberu: 8, Banda: 8, Khajuraho: 7, Fatehpur:7, Maudeha(Ragul): 6, Mahoba:6 & Madla: 5

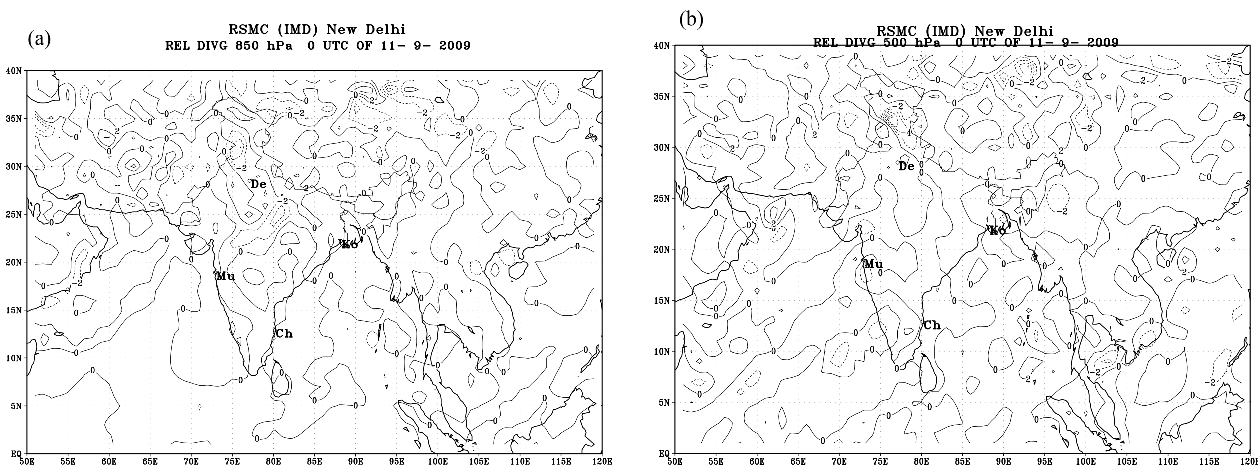
16 Aug 2009 : Rainfall (cm) : Kaimaha: 8, Chillaghat: 7, Banda: 5 & Mahoba: 5



Figs. 3 (a-c). (a) IR Kalpana-1, 0300 UTC and (b) IR Kalpana-1 1200 UTC of 11th September 2009 and (c) Image of Satellite. MET7 image 0600 and 1200 UTC of 10 September 2009. (*Courtesy* : NERC receiving station, University of Dundee)



Figs. 4(a&b). Relative vorticity at 850 hPa, 0000 UTC and (b) 500 hPa, 0000 UTC of 11th September 2009



Figs. 5(a&b). (a) Relative divergence at 850 hPa, 0000 UTC and (b) 500 hPa, 0000 UTC of 11th September 2009

The detailed statistical results of the verification of QPF using 2 × 2 contingency table applying verification method (Wilks, 1995) have also been presented in Table 4, in which Probability of Detection (POD), False Alarm Rate (FAR), Missing Rate (MR), Correct Non-occurrence (C-NON), Critical Success Index (CSI), Biased for Occurrence (BIAS) , Percentage Correct (PC), Heidke Skill Score (HSS) have been observed 0.8 (1), 0.2 (0), 0.2 (0), 0.9 (1), 0.7(1), 1.03 (1), 85.7% (100%), and 0.9(1) respectively, in brackets the values are shown for 100% accurate QPF. These results showed that Synoptic analogue model is able to predict accurate QPF. It has been concluded that the realized AAP are in good agreement with QPF as per synoptic analogue method.

5. Case studies

In this section, typical cases of synoptic situation have been discussed.

5.1. *The Deep Depression / Depression developed over Bay of Bengal after moving west-northwestwards, reached over catchment area as Depression is discussed below :*

5.1.1. *Depression (27 June - 5 July 2005)*

A depression formed over Gangetic West Bengal and adjoining northwest Bay centered close to Kolkata at 1200 UTC of 27. Moving west wards, it lay over Jharkhand, centered near Jamshedpur till 0300 UTC of 29. Subsequently moving in a west-northwesterly direction it lay close to Ranchi at 1200 UTC of 29. It lay close to Daltonganj at 0300 UTC of 30; Sidhi at 1200 UTC of 30 June; Rewa at 0300 UTC of 1st July; and reached east Madhya Pradesh close to Khajuraho from 1200 UTC of 1 to 4 July, and near Nowgong on 5/0000 UTC. It weakened into a well marked low pressure area (LOPAR) over northwest Madhya Pradesh & adjoining west Uttar

Pradesh & east Rajasthan on 6/0000 UTC morning. It moved over to west Uttar Pradesh & neighborhood on 7/0000 UTC. Associated Cycir extended up to 7.6 km above m.s.l caused heavy rainfall in the catchment. The deep convective clouds with vortex could be seen over LYC region in satellite IR image (Fig. 9) on 4th July 2005 at 0600 UTC (*courtesy* : Dundee), which caused intense precipitation over sub-catchment D & E of LYC. The AAP (mm) on 4th July 2005 in sub-catchmentwise follows : A-05 , B-13 , C-11 , D-98 & E-66.

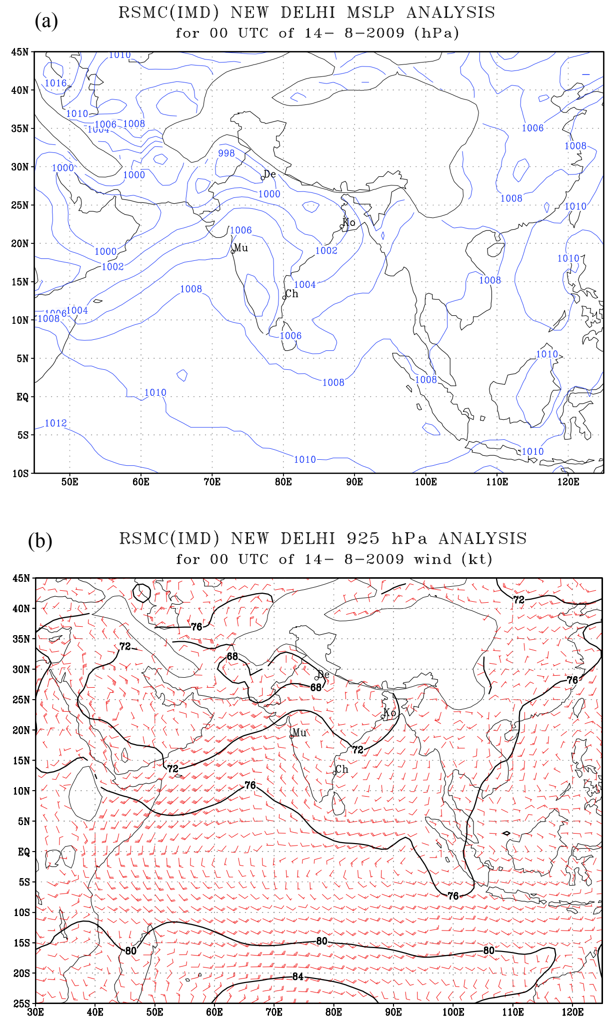
5.2. *Depression over Bay of Bengal reached over catchment area as LOPAR*

5.2.1. *Depression (5-11 September 2009)*

A Deep Depression developed over northwest Bay of Bengal off Orisa coast moved in northerly direction and crossed the west Bengal coast near Digha and lay centered over Gangetic West Bengal about 50 km north of Digha at 0900 UTC of 5. It moved in northwesterly direction and lay over Jharkhand and neighborhood on 6 morning, it further moved in west-northwesterly direction and lay centered near Daltonganj in Jharkhand at 0300 UTC of 7. It weakened into well marked low pressure area (LOPAR) over Jharkhand and adjoining Chhatisgarh, northeast Madhya Pradesh, southeast Uttar Pradesh and adjoining Bihar on 8 morning associated cycir extended up to Mid Tropospheric Levels. It lay over central Madhya Pradesh and neighborhood on 9 morning. It moved northwestwards and lay over north Madhya Pradesh and neighborhood on 10 morning with associated Cycir extended upto 4.5 km a.m.s.l. The axis of monsoon trough on sea level passes through Phalodi, centre of well marked low, Raipur, Bhubaneshwar and thence southeastwards into Bay, Fig. 2(a). Conversion of moisture flux over the area shown in the Fig. 2(b). The well marked low pressure moved north-north-westwards and lay over west Uttar Pradesh & adjoining area on 11 morning, associated Cycir extended upto 3.6 km a.m.s.l. The tracks of the above described Depressions (27 Jun - 5 Jul 2005 & 5 - 11 Sep 2009) are shown in Fig. 1(b).

The Satellite imageries of 10th September at 0600 & 1200 UTC (*courtesy* : Dundee) are shown in Fig. 3(c) and 11th September at 0300 UTC and 1200 UTC show the scattered to broken low and medium clouds with intense convection over the area of LYC, Figs. 3 (a&b). Vorticity and divergence in upper air associated with above described systems are also indicative the rising motion and falling pressure at the surface, presented in Figs. 4 (a&b) and Figs. 5 (a&b).

This LOPAR in association with upper air circulation (CYCIR) extending upto Mid Troposphere



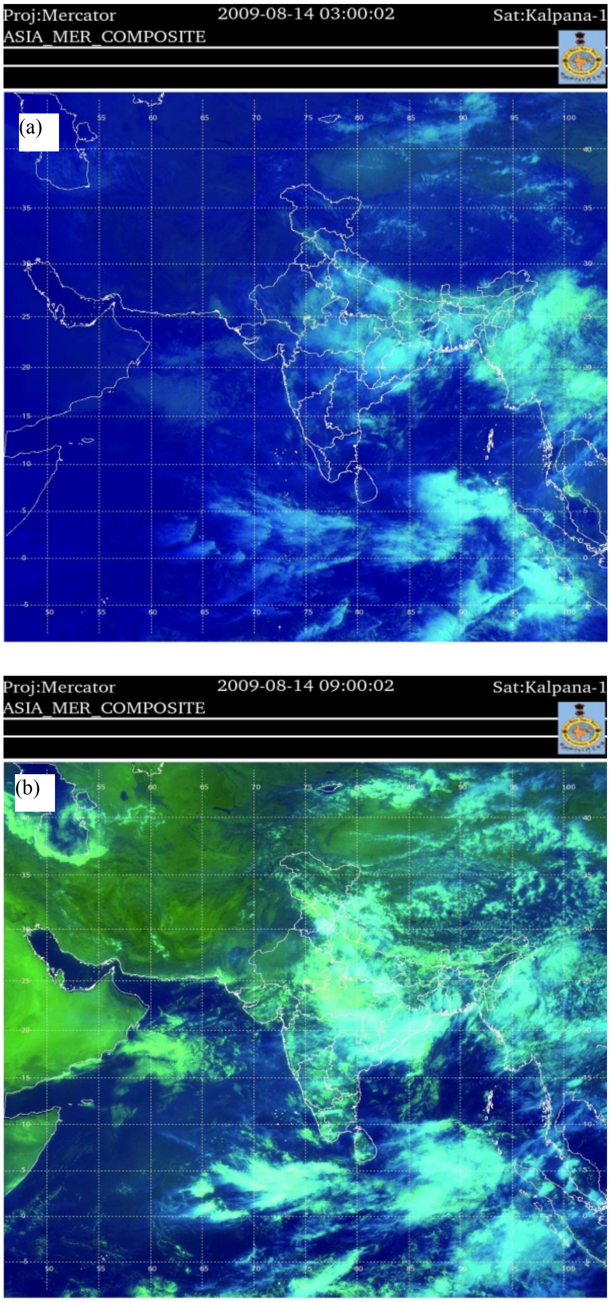
Figs. 6(a&b). (a) Means sea level pressure analysis 0000 UTC and (b) 925 hPa wind analysis 0000 UTC of 14 August 2009

Levels (MTL) moved over catchments resulting rainfall over LYC area.

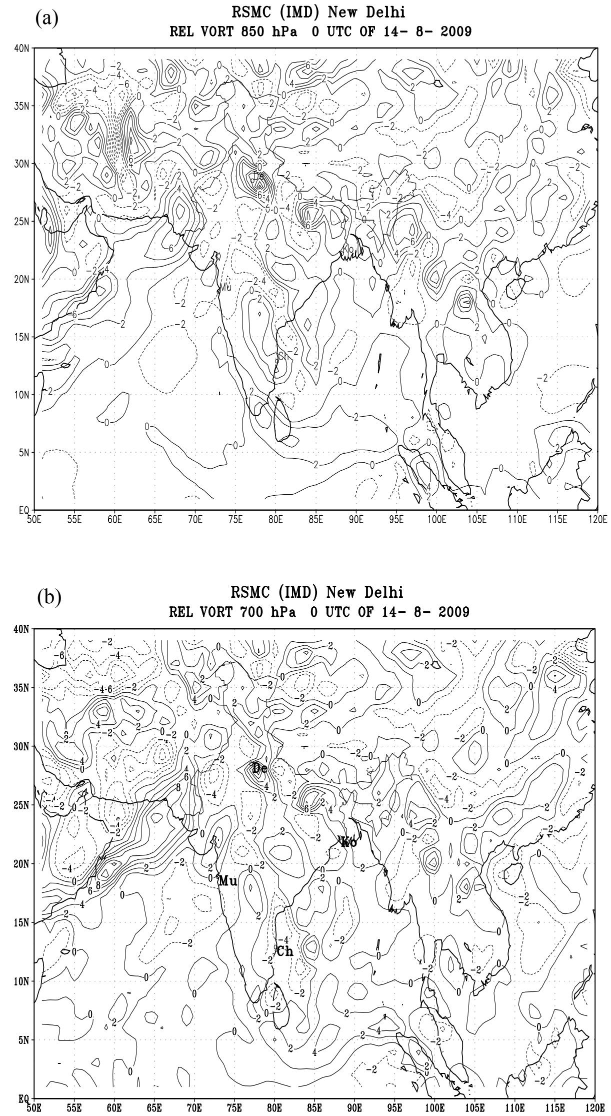
The sub-catchmentwise AAP (in mm) as recorded on 11 Sep 2009 follows: A-29 , B-12 , C- 32 , D-05 & E-32.

5.3. *The upper air cyclonic circulation (CYCIR) during 8-14 Aug 2009*

An upper air cyclonic circulation (Cycir) formed over north Bay of Bengal extending upto Mid Tropospheric Levels lay over northeast Bay of Bengal and neighborhood on 8 morning. It persisted over the same area till 1200 UTC of 10. It moved west northwestwards and lay over north Orissa and neighborhood on 11



Figs. 7(a&b). Kalpana-1 composite imagery (a) 0300 UTC and (b) 0900 UTC of 14th August 2009



Figs. 8 (a&b). Relative vorticity (a) 850 hPa 0000 UTC and (b) 700 hPa 0000 UTC of 14th August 2009

morning. It further moved northwestwards and lay over Chhatisgarh and neighborhood on 12 morning with associated Cycir extending upto 4.6 km a.m.s.l. Subsequently it moved northwestwards and lay over east Uttar Pradesh and neighborhood on 13 morning, associated Cycir extending upto 0.9 km a.m.s.l. It persisted over the same area on 14 morning with associated Cycir extending upto 3.6 km a.m.s.l. Another upper air Cycir lay over Orissa and adjoining Jharkhand with associated cycir extending up Mid Tropospheric Levels. On 14 morning the axis of monsoon trough on sea level passes through Firozpur, Bareilly, Allahabad, Ambikapur, Chandbali and thence southeastwards into Bay. It passes through Ganganagar, Bareilly, Allahabad, Jharsuguda, Bhubaneshwar and thence southeastwards into Bay at 0.9 km a.m.s.l., [Figs. 6 (a&b)]. This lead to scattered to broken low and medium clouds with intense convection over the area [Figs. 7 (a&b)] and yielded good rain over D & E regions. Vorticity in upper air associated with above described system which shows the intensity of vertical motion, leads to the convection as shown in [Figs. 8 (a&b)].

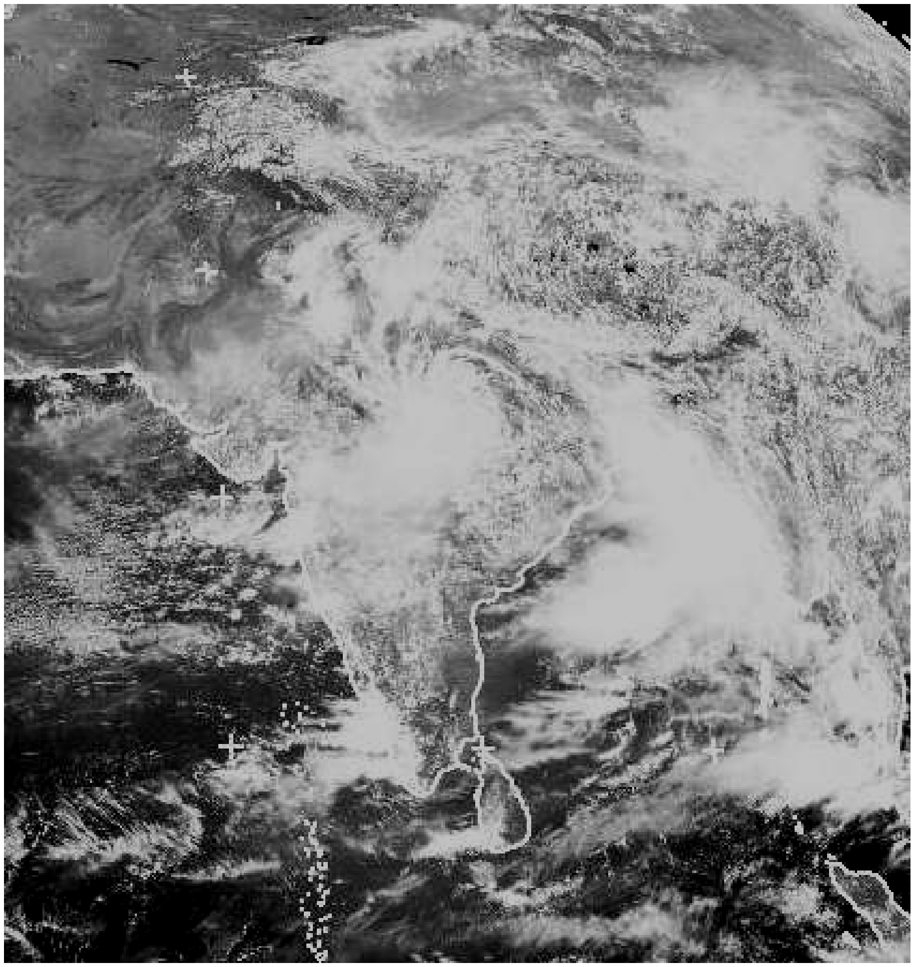


Fig. 9. Image of Satellite. MET5 image 0600 UTC – 04 July 2005 (*Courtesy* : NERC receiving station, University of Dundee)

The AAP (in mm) on 15th August 2009 sub-area wise follows: A-11, B-26, C- 49, D-50 & E-73.

Thus, it is concluded that these systems (Depression/ Lopar/Upper air Cycir) originate generally over northwest Bay of Bengal & adjoining area, move in west to northwestwards direction and reach over catchment area either as a depression or a lopar or as an upper air Cycir and cause copious rain thereby.

6. Conclusions

(*i*) The Synoptic analogue model presented in Table 3, is able to generate QPF in 24 hours advance with greater accuracy and skill. It is possible to improve the forecast accuracy when more data sets pertaining to different synoptic conditions become available. While preparing prediction, its accuracy may be increased by taking into account other inputs like satellite information, NWP model products like Vorticity and Divergence charts, climatology etc.

(*ii*) The frequency of occurrence of different systems can be arranged in the order as follows, S3 > S2> S4 > S1.

(*iii*) The system cyclonic storm/depression S1, Lopar S2 and upper air cycir S3 when embedded cyclonic circulation extending up to MTL can produce rain in the range 51-100 mm. When S1 & S2 are away from the region and S3 extends upto lower level, they yield rain in the range 11-25 mm. The system Deep Depression/ Depression/lopar/upper air cycir develops generally over northwest Bay of Bengal & adjoining area, moves in west to north-westwards direction and reaches over catchment area either as depression or LOPAR or upper air CYCIR thereby yields rain.

(*iv*) The frequency of the depression was observed very low.

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