MAUSAM, **71**, 1 (January 2020), 133-144

551.577.37 (540.41)

Heavy rainfall analysis over Teesta catchment and adjoining areas of Sub-Himalayan West Bengal and Sikkim

G. N. RAHA, S. BANDYOPADHYAY* and S. DAS**

Meteorological Centre, Gangtok – 737 103, India

** Regional Meteorological Centre, Kolkata – 411 005, India*

*** Regional Meteorological Centre, Guwahati – 781 015, India*

(*Received 23 November 2018, Accepted 24 September 2019*)

e mail : itsraha@gmail.com

सार – पहाड़ी क्षेत्र में भारी वर्षा (HRF) का पूर्वानुमान करना प्रचालन पूर्वानुमानकर्ताओं के लिए हमेशा एक चुनौती रही है। सिनॉप्टिक एनालॉग मॉडल (SAM) को भारी वर्षा पूर्वानुमान के लिए एक उपयोगी उपकरण के रूप में माना जाता है जो स्थलाकृति रूप से प्रभावित पहाड़ी क्षेत्रों में होता है। हर मानसून के मौसम में, तीस्ता नदी का जलग्रहण क्षेत्र और उसके आसपास के क्षेत्र उप-हिमालयी पश्चिम बंगाल और सिक्किम (SHWB-S) में आम तौर पर भारी वर्षा की कई परिघटनाएँ होती हैं। उप-हिमालयी पश्चिम बंगाल और सिक्किम (SHWB-S) में तीस्ता नदी के जलग्रहण क्षेत्र और आस-पास के क्षेत्रों पर भारी वर्षा की चेतावनी जारी करने की विधि खोजने के लिए प्राथमिक उद्देश्य के साथ, 18 साल (1998-2015) के आंकड़ों का विश्लेषण करके एक सिनॉप्टिक एनालॉग मॉडल को विकसित किया गया है जिसमें क्षेत्र और भारी वर्षा के बाद के दिन के दैनिक वर्षा डेटा को प्रभावित करने वाली मौजूदा सिनॉप्टिक स्थितियों को शामिल किया गया है। इसके अलावा, भारी वर्षा के वितरण पर विभिन्न सिनोप्टिक प्रणालियों के प्रभाव का भी अध्ययन किया गया है। परिणामों से पता चला कि अगले दिन इस क्षेत्र में प्रेक्षित किए गए भारी वर्षा की परिघटना और जारी किए गए दैनिक भारी वर्षा चेतावनियाँ सुसंबंधित हैं।

ABSTRACT. Heavy rainfall (HRF) forecasting in hilly region is always a challenge to the operational forecasters. Synoptic Analogue Model (SAM) is considered as one of the useful tools for HRF forecasting in topographically influenced hilly regions. In every monsoon season, the Teesta river catchment and its adjoining areas in Sub-Himalayan West Bengal and Sikkim (SHWB-S) generally receive several events of HRF. With the primary objective to find the method to issue HRF warning over Teesta river catchment and adjoining areas in SHWB-S, a SAM has been developed by analyzing 18 years (1998-2015) data comprising prevailing synoptic situations affecting the area and daily rainfall data of subsequent day of HRF. In addition, impact of different synoptic systems on the distribution of HRF has also been studied. The results revealed that there exists a good agreement between daily HRF warnings issued with the corresponding HRF event observed over this region on the next day.

Key words – Synoptic analog model, Teesta basin, Heavy rainfall warning.

1. Introduction

Teesta River Catchment and its adjoining areas in Sub-Himalayan West Bengal and Sikkim (SHWB-S) is one such area where Heavy rainfall (HRF) is a very common phenomenon during south-west monsoon season (JJAS). These HRF activities often results water induced hazards like flash floods and landslides causing significant loss of lives and damage to the properties. Therefore, accurate forecasting of HRF in SHWB-S is of vital importance in general and of great challenge to the operational forecasters, in particular. The challenge of timely and location specific forecasting of HRF in the area increases due its high elevated mountains. Topography itself has a profound effect on spatial patterns of precipitation both globally and regionally (Smith, 1979). The interaction of atmosphere with topography is well documented by Durran, 1986; Simpson, 1987. Houze, 1993 showed that the vertical profiles of temperature and moisture content and the velocity of the incoming air, which vary from storm to storm, as well as characteristics of the topography, including the length, width and height of the mountain range, determine how the atmosphere interacts with the mountains.

Many studies by several authors (Abbi *et al*., 1970; Rao *et al.*, 1970; Abbi *et al.*, 1979; Lal *et al.*, 1983; Daoud *et al*., 2011) suggested that synoptic analog model (SAM) to estimate the quantitative precipitation over the river catchments. Obled *et al*. (2002), Gibergans-Baguena and Llasat (2007), Bliefernicht and Bardossy (2007) have also shown the usefulness of the analog models in forecasting the precipitation. Gao *et al*. (2014) have presented an analogue method to detect the occurrence of heavy precipitation events without relying on modeled precipitation and showed that the method captured the HRF events very well. The rainfall characteristics of the Teesta river catchment and adjoining areas in SHWB-S has been studied by Bhattacharya and Bhattacharya ,1980; Dhar *et al.* (1996); Biswas and Bhadram, 1984. Lahiri (1981) have discussed the method of forecasting of rain and floods in the Teesta River. Rao *et al*. (1997) have shown that statistical analog procedure gives a good idea for predicting average areal precipitation semi-quantitatively for Teesta basin.

In this present study, daily rainfall data and synoptic situations prevailed on the previous day over SHWB-S during south-west monsoon season (1st June to 30th September) for the period 1998 to 2015 have been considered to find out the existence of correlation between them, if any, so that HRF warning over this region can be issued with more accuracy. In addition, impact of different synoptic systems in the distribution of HRF (65 mm and above) during this season over Teesta basin & adjoining areas in SHWB-S has also been studied.

2. The study area

The River Teesta originates in the glacial mountains of the state of Sikkim. It is flowing through the districts of Darjeeling and Jalpaiguri and then enters the Rangpur Division of Bangladesh. The Teesta is a perennial, rain and snow fed river. The Teesta is classified as a high-altitude basin in the state of Sikkim, with nearly one fourth of the basin area at an elevation of 4,000 to 5,000 meters and more than 59 per cent of the catchment area above 3,000 meters. The Teesta is joined by a number of tributaries such as the Leesh, the Geesh, the Chel, the Neora and the Karala in the Sub-Himalayan plains before entering Bangladesh. The transboundary basin of the Teesta River encompasses 12,159 square kilometers, of which 83% are in India and remaining 17% are in Bangladesh. About, 66% of the river basin lies in hilly parts of Sikkim (86%) and West Bengal (14%). The upper catchment of the Teesta Basin in Sikkim is prone to sudden variations in rainfall and temperature due to the high altitude and mountainous topography. Middle and lower catchment are open to the moist southerly/ south westerly monsoon current. Frequency of the HRF is highest along Middle and lower catchment which lies in the foot hills (wind-ward side) of Himalayas. The rain gauge stations over the Teesta catchment and adjoining areas of SHWB-S are shown in Fig. 1.

3. Data and methodology

The synoptic situations along with the HRF realized on the next day over the Teesta catchment and adjoining areas of SHWB-S during south-west monsoon season of 1998-2015 have been utilized for the present study. The synoptic situations recorded in the mid-day inferences issued by Area Cyclone Warning Centre (ACWC), Regional Meteorological Centre, Kolkata have been utilized. Based on the closeness to the catchment and intensity of the systems which have most significant impacts on the rainfall activity over the catchment and adjoining areas have been taken into consideration. To find the impact of different synoptic situations on the frequency of HRF (more than 64.4 mm) event over different locations, the study area has been divided into three portions *viz*., Upper Portion, Middle Portion and Lower Portion. Accordingly, all the rain gauge stations (9) of Sikkim in the Upper Portion; Middle Portion consists of 14 rain gauge stations whereas 12 rain gauges in the Lower Portion are considered for of the purpose.

4. Results and analysis

4.1. *Salient features of rainfall distribution over Teesta basin and adjoining areas of SHWB-S*

HRF event over this area is frequent during the monsoon season and induces many weather and terrain related hazards. Most of the parts of state Sikkim and Darjeeling district falls in mountainous region where as Jalpaiguri, Alipoorduar and Coochbehar districts are at the foot hills of Himalayas. On an average, 250-400 cm rainfall occurred during the months of south-west monsoon season (June to September) over various rain gauge stations of this region. Frequencies of heavy to very heavy rain falls over these stations are also considerably high, about 10-20 days during the south-west monsoon season.

Primarily, due to prolonged thunderstorm activity, this area receives good amount of rainfall during the late night & early morning of a day. On the other hand, the typical orographic features in combination with the moisture incursion from Bay of Bengal due to southerly/ south-easterly flow in the lower levels are the deciding factors for causing HRF activity on daily scale over this region. Even in absence of any synoptic situations invariably after a gap of two / three days of dry spell, strong instability in the atmosphere along with southerly moisture flow from Bay of Bengal and its interaction with the orography causes significant rainfall activity over this region.

Some salient features of rainfall activity over Teesta catchment and adjoining areas of SHWB-S during south-west monsoon season (1998-2015) are summarized in the Table 1. Table 1 reveals that

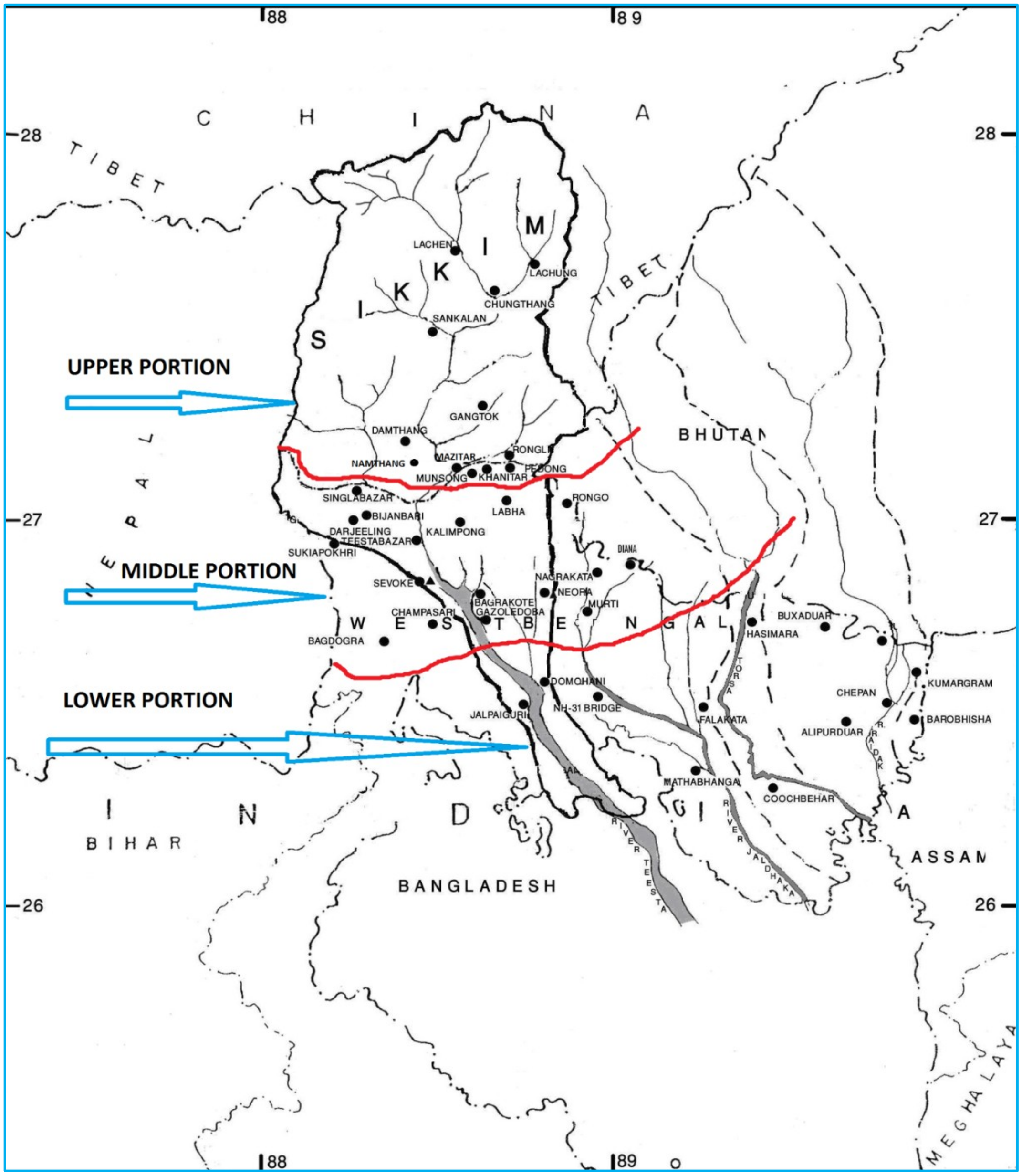

Fig. 1. Teesta catchment along with rain gauge stations over SHWB-S

during the study period, on an average Gangtok and Rongo experience the highest number of rainy days (99) whereas Neora rainfall observatory recorded highest one day rainfall (53 cm on 18th June, 1998) during the months of south-west monsoon season. On the other hand, it is seen that the station Rongo receives highest amount of average rainfall (427 cm) whereas the mean frequencies of HRF is maximum over Buxaduar (21) during the months of south-west monsoon season. Buxaduar also experienced highest number (total 33) of days with extremely HRF during the period of study 1998-2015.

4.2. *Distribution of HRF events over Teesta basin and adjoining areas of SHWB-S*

The Analysis of HRF distribution over Teesta catchment and adjoining areas using SAM method for the period 1998 to 2015 are summarized in the Table 2. From this table, following points may be inferred:

(a) Total seventy one (71) types of synoptic situations have been identified and shown in Table 8. Out of 2196 days during 1998 to 2015 of monsoon months (June to September), it has been

TABLE 1

Various features of rainfall distribution during southwest monsoon season (1998-2015) over Teesta basin and adjoining areas in SHWB & Sikkim

Area	Station	Lat. (N)	Long. (E)	Altitude (m)	Average seasonal rainfall (mm)	Mean frequency of rainy days	Average no. of days with rainfall 65 mm & above	Highest rainfall recorded (mm)	No. of days of extreme HRF
Upper Portion (Sikkim)	Gangtok	27° 20'	88° 36'	1765	2333	99	4	188	0
	Tadong	27° 19'	88° 36'	1322	1996	91	3	213	1
	Chungthang	27° 36'	88° 39'	1131	1284	91	1	101	0
	Mangan	27° 30'	88° 32'	1166	2105	90	4	197	0
	Damthung	27° 14'	88° 23'	1981	2017	86	5	156	0
	Namthung	27° 10'	88° 30'	1350	1382	65	3	240	3
	Mazitar	27° 11'	88° 30'	340	1261	62	3	159	0
	Khanitar	27° 11'	88° 30'	302	1341	65	3	181	0
Middle Portion (West Bengal)	Lava	27° 04'	88° 40'	2621	2670	88	10	271	3
	Singlabazar	27° 07'	88° 14'	240	1270	61	3	178	0
	Sevoke	26° 53'	88° 28'	152	3388	85	17	332	15
	Rongo	27° 10'	88° 32'	1189	4265	99	20	322	13
	Neora	26° 52'	88° 46'	164	3037	83	13	532	11
	Nagrakata	26° 54'	88° 55'	229	3012	84	14	324	13
	Murti	26° 51'	88° 50'	143	2898	80	13	294	11
	Bagrakote	26° 56'	88° 32'	205	3330	85	15	310	10
	Diana	26° 56'	89° 00'	200	3050	83	13	404	20
	Champasari	26° 43'	88° 25'	123	2805	76	14	241	1
	Bagdogra	26° 38'	88° 19'	131	2677	74	13	254	6
	Darjeeling	27° 03'	88° 16'	2127	1772	70	6	220	1
	Kalimpong	27° 04'	88° 28'	1209	1598	64	5	189	0
	Gazoldoba	26° 45'	88° 40'	110	2961	72	15	396	8
Lower Portion (West Bengal)	Jalapiguri	26° 32'	88° 43'	83	2708	71	13	474	16
	Domohoni	26° 33'	88° 45'	85	2550	71	12	347	12
	NH-31	26° 35'	88° 56'	82	2208	67	10	423	6
	Falakata	26° 31'	89° 12'	63	2159	55	11	312	11
	Mathabhanga	26° 20'	89° 14'	50	2127	64	9	326	10
	Chepan	27° 19'	89° 39'	55	2693	65	13	467	21
	Alipurduar	27° 29'	89° 31'	46	2503	63	12	351	17
	Kumargram	27° 37'	89° 48'	76	2998	64	15	370	27
	Buxaduar	27° 54'	89° 35'	814	3029	62	15	401	33
	Barobhisha	27° 31'	89° 48'	57	2556	65	12	375	18
	Hasimara	27° 40'	89° 20'	119	3045	76	15	390	19
	Cooch Behar	26° 20'	89° 28'	43	2388	70	10	346	14

found that the study area received HRF events at (*i*) Isolated places in 1165 days (53%), (*ii*) A few places in 203 days (9%) and (*iii*) Many places in only 15 days (1%).

(b) During the study period, location wise occurrences of HRF events are stated below:

Upper Portions: (*i*) At Isolated places in 171 days (8%), (*ii*) At a few places in 102 days (5%) and (*iii*) At many places only in 4 days (0%).

Middle Portions: (*i*) At Isolated places in 718 days (33%), (*ii*) At a few places in 302 days (14%) and (*iii*) At many places only in 43 days (2%).

TABLE 2

Summary of heavy/very heavy/extremely rainfall events during the period 1998 to 2015

Distribution	Frequency of event [% of event]			
	Total Study Area	Upper Portion	Middle Portion	Lower Portion
HRF (more than 64.4 mm)				
Isolated Places	1165[53]	171[8]	718[33]	474[22]
A Few Places	203[9]	102[5]	302[14]	295[13]
Many Places	15[1]	4[0]	43[2]	52[2]
Very HRF (more than 115.5 mm)				
Isolated Places	648[30]	25[1]	343[16]	288[13]
A Few Places	39[2]	13[1]	94[4]	109[5]
Many Places	0[0]	0[0]	3[0]	17[1]
Extremely HRF (more than 204.4 mm)				
Isolated Places	202[9]	3[0]	77[4]	108[5]
A Few Places	1[0]	0[0]	3[0]	22[1]
Many Places	0[0]	0[0]	0[0]	1[0]

Lower Portions: (*i*) At Isolated places in 474 days (22%), (*ii*) At a few places in 295 days (13%) and (*iii*) At many places only in 52 days (2%).

(c) Table 2 reveals that during the study period, frequency of Very HRF (more than 115.5 mm) event at many places over Teesta catchment and adjoining areas in Sub-Himalayan West Bengal was nil. However, it has been found that the Very HRF occurred at (*i*) Isolated places in 648 days (30%) and (*ii*) At a few places in 39 days (2%).

(d) Location wise occurrence of Very HRF events which were observed during the study period are:

Upper Portions: (*i*) At Isolated places in 25 days (1%) and (*ii*) At a few places only in 13 days (1%).

Middle Portions: (*i*) At Isolated places in 343 days (33%), (*ii*) At a few places in 94 days (4%) and (*iii*) At many places only in 3 days.

Lower Portions: (*i*) At Isolated places in 288 days (13%), (*ii*) At a few places in 109 days (5%) and (*iii*) At many places only in 17 days (1%).

(e) It is also seen that that out of 2196 days during monsoon months (JJAS) of 1998 to 2015, the entire study area received extremely HRF (more than 204.4 mm) event at isolated places in 202 days (9%) in which Higher portions received only in 3-days, Middle Portions in 77 days (4%) and Lower portions in 108 days (5%).

4.3. *Most Favourable systems for occurrence of HRF events over Teesta basin and adjoining areas of SHWB-S*

The most favourable synoptic systems producing HRF events over Teesta basin & adjoining areas in SHWB-S for the period 1998 to 2015 are summarized in the Table 3. From this table, following points may be inferred:

(a) Total 12-numbers of most favorable synoptic systems (with frequencies more than 1% of total study period) have been identified for the occurrence HRF (at least over isolated places) over the entire area of study period. These are denoted as **S1**: Trough over SHWB & Sikkim - 89% (270 out of 302) occasions; **S2**: Upper air cyclonic circulation along with trough passing through SHWB & Sikkim - 90% (28 out of 31) occasions; **S3**: Upper air cyclonic circulation over Bihar along with trough passing through SHWB & Sikkim - 94% (48 days out of 51 days) occasions; **S4**: Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 91% (21 days out of 23 days) occasions; **S5**: Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - 74% (32 out of 43) occasions; **S6**: Upper air cyclonic circulation over Bihar - 75% (66 out of 88) occasions; **S7**: Upper air cyclonic circulation over East Uttar Pradesh & adjoining Bihar - 70% (21 out of 30) occasions; **S8**: Trough over Gangetic West Bengal - 67% (103 out of 153) occasions; **S9:** Upper air cyclonic circulation over SHWB and Sikkim - 65% (24 out of 37) occasions; **S10**: Low over

TABLE 3

Most favourable systems producing at least HRF event during the period 1998 to 2015

Total Study Area		Upper Portion		Middle Portion		Lower Portion	
System	Percentage [No. of events (No. of HRF events)]	System	Percentage [No. of events (No. of HRF events)]	System	Percentage [No. of events (No. of HRF events)]	System	Percentage [No. of events (No. of HRF events)]
S3	94[51(48)]	S4	26[23(6)]	S3	75[51(38)]	S2	71[31(22)]
S4	91[23(21)]	S11	25[63(16)]	S1	74[302(224)]	S3	65[51(33)]
S2	90[31(28)]	S1	20[302(60)]	S4	70[23(16)]	S1	59[302(179)]
S1	89[302(270)]	S9	19[37(7)]	S2	61[31(19)]	S4	57[23(13)]
S6	75[88(66)]	S7	17[29(5)]	S9	54[37(20)]	S5	51[43(22)]
S5	74[43(32)]	S8	17[153(26)]	**S6**	52[88(46)]	S8	48[153(73)]
S7	72[29(21)]	S3	16[51(8)]	S11	51[63(32)]	**S6**	44[88(39)]
S11	70[63(44)]	S2	16[31(5)]	S5	51[43(22)]	S12	43[35(15)]
S8	67[153(103)]	S10	13[54(7)]	S12	50[34(17)]	S7	41[29(12)]
S9	65[37(24)]	-	-	-	-	-	-
S10	63[54(34)]	-	-	-	-	-	-
S12	53[34(18)]	-	-	-	-	-	-

TABLE 4

Impact of different synoptic systems on the distribution of HRF over Teesta basin and adjoining areas in SHWB & Sikkim during the period 1998 to 2015

Synoptic system	Impact of the system to HRF			Impact of the system to Very HRF			Impact of the system to Extremely HRF		
	Total cases (% of cases when HRF realized)			Total cases (% of cases when very HRF realized)			Total cases (% of cases when extremely HRF realized)		
	Isolated	Few	Many	Isolated	Few	Many	Isolated	Few	Many
S1	184(61)	80(26)	6(2)	161(53)	19(6)	0(0)	76(25)	1(0)	0(0)
S2	23(74)	3(10)	2(6)	16(52)	2(6)	0(0)	6(19)	0(0)	0(0)
S3	38(75)	9(18)	1(2)	29(57)	1(2)	0(0)	5(10)	0(0)	0(0)
S4	16(70)	4(17)	1(4)	10(43)	1(4)	0(0)	2(9)	0(0)	0(0)
S5	29(67)	3(7)	0(0)	13(30)	2(5)	0(0)	6(14)	0(0)	0(0)
S6	64(74)	2(2)	0(0)	30(35)	0(0)	0(0)	6(7)	0(0)	0(0)
S7	16(55)	5(17)	0(0)	8(28)	0(0)	0(0)	1(3)	0(0)	0(0)
S8	89(58)	14(9)	0(0)	56(37)	3(2)	0(0)	15(10)	0(0)	0(0)
S9	23(64)	1(3)	0(0)	10(28)	0(0)	0(0)	2(6)	0(0)	0(0)
S10	32(59)	2(4)	0(0)	11(20)	1(2)	0(0)	4(7)	0(0)	0(0)
S11	38(60)	5(8)	1(2)	20(32)	1(2)	0(0)	5(8)	0(0)	0(0)
S12	18(53)	0(0)	0(0)	1(3)	0(0)	0(0)	0(0)	0(0)	0(0)

Jharkhand - 63% (34 out of 54) occasions; **S11:** North-South trough of low/trough in monsoon westerlies - 70% (44 out of 63) occasions; and **S12**: Low over Gangetic West Bengal - 53% (18 out of 34) occasions.

(b) Most favourable synoptic systems (with frequencies more than 5) for the occurrence HRF (atleast over isolated places) over different locations in study area were:

TABLE 5

Impact of different synoptic systems on the distribution of HRF over the upper portion of the study area during the period 1998 to 2015

Synoptic system	Impact of the system to HRF Total cases (% of cases when HRF realized)			Impact of the system to Very HRF Total cases (% of cases when very HRF realized)			Impact of the system to Extremely HRF Total cases (% of cases when extremely HRF realized)		
	Isolated	Few	Many	Isolated	Few	Many	Isolated	Few	Many
S1	34(11)	23(8)	3(1)	6(2)	5(2)	0(0)	1(0)	0(0)	0(0)
S2	1(3)	4(13)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
S3	5(10)	3(6)	0(0)	1(2)	0(0)	0(0)	0(0)	0(0)	0(0)
S4	3(13)	3(13)	0(0)	1(4)	0(0)	0(0)	0(0)	0(0)	0(0)
S5	2(5)	0(0)	0(0)	1(2)	0(0)	0(0)	1(2)	0(0)	0(0)
S6	6(7)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
S7	3(10)	2(7)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
S8	18(12)	8(5)	0(0)	2(1)	1(1)	0(0)	1(1)	0(0)	0(0)
S9	6(17)	1(3)	0(0)	0(0)	1(3)	0(0)	0(0)	0(0)	0(0)
S10	5(9)	2(4)	0(0)	1(2)	1(2)	0(0)	0(0)	0(0)	0(0)
S11	8(13)	8(13)	0(0)	4(6)	0(0)	0(0)	0(0)	0(0)	0(0)
S12	1(3)	1(3)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)

TABLE 6

Impact of different synoptic systems on the distribution of HRF over the middle portion of the study area during the period 1998 to 2015

Synoptic system	Impact of the system to HRF Total cases (% of cases when HRF realized)			Impact of the system to Very HRF Total cases (% of cases when very HRF realized)			Impact of the system to Extremely HRF Total cases (% of cases when extremely HRF realized)		
	Isolated	Few	Many	Isolated	Few	Many	Isolated	Few	Many
S1	126(42)	78(26)	20(7)	93(31)	37(12)	2(1)	35(12)	2(1)	0(0)
S2	11(35)	7(23)	1(3)	9(29)	3(10)	0(0)	4(13)	0(0)	0(0)
S3	19(37)	16(31)	3(6)	16(31)	2(4)	0(0)	2(4)	0(0)	0(0)
S4	8(35)	7(30)	1(4)	7(30)	0(0)	0(0)	0(0)	0(0)	0(0)
S5	16(37)	5(12)	1(2)	8(19)	2(5)	0(0)	2(5)	0(0)	0(0)
S6	32(37)	14(16)	0(0)	17(20)	1(1)	0(0)	4(5)	0(0)	0(0)
S7	6(21)	6(21)	0(0)	4(14)	0(0)	0(0)	1(3)	0(0)	0(0)
S8	52(34)	20(13)	1(1)	32(21)	4(3)	0(0)	4(3)	0(0)	0(0)
S9	17(47)	3(8)	0(0)	8(22)	0(0)	0(0)	2(6)	0(0)	0(0)
S10	18(33)	8(15)	0(0)	7(13)	2(4)	0(0)	2(4)	0(0)	0(0)
S11	26(41)	6(10)	0(0)	8(13)	3(5)	0(0)	0(0)	0(0)	0(0)
S12	15(44)	2(6)	0(0)	1(3)	0(0)	0(0)	0(0)	0(0)	0(0)

Upper Portions: (*i*) Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 26% (6 out of 23) occasions; (*ii*) North-South trough of low/trough in monsoon westerlies - 25% (16 out of 63) occasions; (*iii*) Trough over SHWB-S - 20% (60 out of 302) occasions; (*iv*) Upper air cyclonic circulation over SHWB-S - 19% (7 out of 37) occasions; (*v*) Upper air cyclonic circulation over East

TABLE 7

Impact of different synoptic systems on the distribution of HRF over the lower portion of the study area during the period 1998 to 2015

Synoptic System	Impact of the system to HRF Total cases (% of cases when HRF realized)			Impact of the system to Very HRF Total cases (% of cases when very HRF realized)			Impact of the system to Extremely HRF Total cases (% of cases when extremely HRF realized)		
	Isolated	Few	Many	Isolated	Few	Many	Isolated	Few	Many
S1	82(27)	81(27)	16(5)	67(22)	36(12)	11(4)	30(10)	14(5)	0(0)
S2	13(42)	7(23)	2(6)	8(26)	2(6)	1(3)	2(6)	0(0)	0(0)
S3	17(33)	14(27)	2(4)	14(27)	7(14)	0(0)	3(6)	0(0)	0(0)
S4	8(35)	4(17)	1(4)	6(26)	1(4)	1(4)	2(9)	0(0)	0(0)
S5	12(28)	9(21)	1(2)	8(19)	2(5)	0(0)	3(7)	0(0)	1(2)
S6	31(36)	6(7)	2(2)	12(14)	2(2)	0(0)	2(2)	0(0)	0(0)
S7	8(28)	2(7)	2(7)	3(10)	3(10)	0(0)	1(3)	0(0)	0(0)
S8	41(27)	26(17)	6(4)	26(17)	9(6)	1(1)	8(5)	3(2)	0(0)
S9	9(25)	2(6)	1(3)	1(3)	1(3)	0(0)	0(0)	0(0)	0(0)
S10	9(17)	5(9)	1(2)	4(7)	0(0)	1(2)	1(2)	1(2)	0(0)
S11	11(17)	13(21)	0(0)	8(13)	3(5)	2(3)	5(8)	0(0)	0(0)
S12	2(6)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)

Uttar Pradesh & adjoining Bihar - 17% (5 out of 29) occasions; (*vi*) Trough over Gangetic West Bengal - 17% (26 out of 153) occasions; (*vii*) Upper air cyclonic circulation over Bihar along with trough passing through SHWB & Sikkim - 16% (8 out of 51) occasions; (*viii*) Upper air cyclonic circulation along with trough passing through SHWB & Sikkim - 16% (5 out of 31) occasions and (*ix*) Low over Jharkhand - 13% (7 out of 54) occasions.

Middle Portions: (*i*) Upper air cyclonic circulation over Bihar along with trough passing through SHWB & Sikkim - 75% (38 out of 51) occasions; (*ii*) Trough over SHWB-S - 74% (224 out of 302) occasions; (*iii*) Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 70% (16 out of 23) occasions; (*iv*) Upper air cyclonic circulation along with trough passing through SHWB-S - 61% (19 out of 31) occasions; (*v*) Upper air cyclonic circulation over SHWB-S - 54% (20 out of 37) occasions; (*vi*) Upper air cyclonic circulation over Bihar - 52% (46 out of 88) occasions; (*vii*) North-South trough of low/trough in monsoon westerlies - 51% (32 out of 63) occasions; (*viii*) Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - 51% (22 out of 43) occasions and (*ix*) Low over Gangetic West Bengal - 50% (17 out of 34) occasions.

Lower Portions: (*i*) Upper air cyclonic circulation along with trough passing through SHWB-S - 71% (22 out of 31) occasions; (*ii*) Upper air cyclonic circulation over Bihar along with trough passing through SHWB-S - 65% (33 out of 51) occasions; (*iii*) Trough over SHWB & Sikkim - 59% (179 out of 302) occasions; (*iv*) Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 57% (13 out of 23) occasions; (*v*) Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - 51% (22 out of 43) occasions; (*vi*) Trough over Gangetic West Bengal - 48% (73 out of 153) occasions; (*vii*) Upper air cyclonic circulation over Bihar - 44% (39 out of 88) occasions; (*viii*) Upper air cyclonic circulation over West central Bay, Andhra Pradesh and Telengana - 43% (15 out of 35) occasions and (*ix*) Upper air cyclonic circulation over East Uttar Pradesh & adjoining Bihar - 41% (12 out of 29) occasions.

4.4. *Impact of important synoptic systems for occurrence of HRF events over Teesta basin and adjoining areas of SHWB-S*

(a) The impact of various important synoptic systems on the HRF activities over Teesta basin & adjoining areas in SHWB-S for the period 1998 to 2015 are summarized in the Table 4. From this table, following points may be inferred:

(*i*) Upper air cyclonic circulation over Bihar along with trough passing through SHWB-S responsible for

TABLE 8

Various synoptic systems identified over SHWB & Sikkim during 1998 to 2015

S. No.	Synoptic System	S. No.	Synoptic System
1.	Low over SHWB & Sikkim	29.	Low over Jharkhand and trough passing through SHWB & Sikkim
2.	Low over Bihar	30.	Low over Chhattisgarh & East Madhya Pradesh and trough passing through SHWB & Sikkim
3.	Low over Jharkhand	31.	Low over East Uttar Pradesh & adjoining Bihar and trough passing through SHWB & Sikkim
4.	Low over Gangetic West Bengal	32.	Low over Uttar Pradesh and trough passing through SHWB & Sikkim
5.	Low over Bangladesh	33.	Low over Northwest Madhya Pradesh and trough passing through SHWB & Sikkim
6.	Low over Assam& Meghalaya	34.	Low over West central Bay Andhra Pradesh and Telengana and trough passing through SHWB & Sikkim
7.	Low over North Bay of Bengal	35.	Upper Air Cyclonic Circulation over SHWB & Sikkim and trough passing through Gangetic West Bengal
8.	Low over Orissa	36.	Upper Air Cyclonic Circulation over Bihar and trough passing through Gangetic West Bengal
9.	Low over Chhattisgarh & East Madhya Pradesh	37.	Low over West central Bay. Andhra Pradesh and Telengana
10.	Low over East Uttar Pradesh & adjoining Bihar	38.	Depression over Bihar
11.	Low over Uttar Pradesh	39.	Depression over Jharkhand
12.	Low over Northwest Madhya Pradesh	40.	Depression over Gangetic West Bengal
13.	Upper Air Cyclonic Circulation over Bihar	41.	Depression over Bangladesh
14.	Upper Air Cyclonic Circulation over Jharkhand	42.	Depression over North Bay of Bengal
15.	Upper Air Cyclonic Circulation over Gangetic West Bengal	43.	Depression over Orissa
16.	Upper Air Cyclonic Circulation over Bangladesh	44.	Depression over Chhattisgarh & East Madhya Pradesh
17.	Upper Air Cyclonic Circulation over Assam& Meghalaya	45.	Depression over Uttar Pradesh
18.	Upper Air Cyclonic Circulation over North Bay of Bengal	46.	Depression over Northwest Madhya Pradesh
19.	Upper Air Cyclonic Circulation over Orissa	47.	Depression over West central Bay. Andhra Pradesh and Telengana
20.	Upper Air Cyclonic Circulation over Chhattisgarh & East Madhya Pradesh	48.	Upper Air Cyclonic Circulation over SHWB & Sikkim
21.	Upper Air Cyclonic Circulation over East Uttar Pradesh & adjoining Bihar	49.	Trough passing through SHWB & Sikkim
22.	Upper Air Cyclonic Circulation over Uttar Pradesh	50.	Trough passing through Gangetic West Bengal
23.	Upper Air Cyclonic Circulation over Northwest Madhya Pradesh	51.	Trough passing through Assam& Meghalaya
24.	Upper Air Cyclonic Circulation over West central Bay. Andhra Pradesh and Telengana	52.	Trough passing through Orissa
25.	Upper Air Cyclonic Circulation over West central Bay Andhra Pradesh and Telengana and trough passing through SHWB & Sikkim	53.	Upper Air Cyclonic Circulation over SHWB & Sikkim and trough passing through SHWB & Sikkim
26.	North-South trough of low/ trough in monsoon westerlies	54.	Upper Air Cyclonic Circulation over Bihar and trough passing through SHWB & Sikkim
27.	Low over SHWB & Sikkim and trough passing through SHWB & Sikkim	55.	Upper Air Cyclonic Circulation over Jharkhand and trough passing through SHWB & Sikkim
28.	Low over Bihar and trough passing through SHWB & Sikkim	56.	Upper Air Cyclonic Circulation over Bangladesh and trough passing through SHWB & Sikkim

TABLE 8 (*Contd.*)

S. No.	Synoptic System	S. No.	Synoptic System
57.	Upper Air Cyclonic Circulation over Orissa and trough passing through SHWB & Sikkim	65.	Upper Air Cyclonic Circulation over North Bay of Bengal and trough passing through Gangetic West Bengal
58.	Upper Air Cyclonic Circulation over Chhattisgarh & East Madhya Pradesh and trough passing through SHWB & Sikkim	66.	Upper Air Cyclonic Circulation over Orissa and trough passing through Gangetic West Bengal
59.	Upper Air Cyclonic Circulation over East Uttar Pradesh & adjoining Bihar and trough passing through SHWB & Sikkim	67.	Upper Air Cyclonic Circulation over Chhattisgarh & East Madhya Pradesh and trough passing through Gangetic West Bengal
60.	Upper Air Cyclonic Circulation over Northwest Madhya Pradesh and trough passing through SHWB & Sikkim	68.	Upper Air Cyclonic Circulation over East Uttar Pradesh & adjoining Bihar and trough passing through Gangetic West Bengal
61.	Upper Air Cyclonic Circulation over Jharkhand and trough passing through Gangetic West Bengal	69.	Upper Air Cyclonic Circulation over Uttar Pradesh and trough passing through Gangetic West Bengal
62.	Upper Air Cyclonic Circulation over Gangetic West Bengal and trough passing through Gangetic West Bengal	70.	Upper Air Cyclonic Circulation over Northwest Madhya Pradesh and trough passing through Gangetic West Bengal
63.	Upper Air Cyclonic Circulation over Bangladesh and trough passing through Gangetic West Bengal.	71.	Upper Air Cyclonic Circulation over West central Bay Andhra Pradesh and Telengana and trough passing through Gangetic West Bengal
64.	Upper Air Cyclonic Circulation over Assam& Meghalaya and trough passing through Gangetic West Bengal		

occurrence of HRF at isolated, at a few and at many places respectively in 28 (75%), 9 (18%) and 1 (2%) days; for very HRF at isolated and at a few places respectively in 29 (57%) and 1 (2%) day whereas for extremely HRF at isolated in 5 (10%) days, (*ii*) Upper air cyclonic circulation along with trough passing through SHWB-S - contributes HRF at isolated, at a few and at many places respectively in 23 (74%), 3 (10%) and 2 (6%) days; very HRF at isolated and at a few places respectively in 16 (52%) and 2 (6%) days where as extremely HRF at isolated places in 6 (19%) days, (*iii*) Upper air cyclonic circulation over Bihar- contributes HRF at isolated and at a few places in 64 (74%) and 2 (2%) days; very HRF at isolated places in 30 (35%) days where as extremely HRF at isolated places in 6 (7%) days, (*iv*) Upper air cyclonic circulation over Bihar along with trough passing through Gangetic West Bengal - contributes HRF at isolated, at a few and at many places respectively in 16 (70%), 4 (17%) and 1 (4%) days; very HRF at isolated and at a few places respectively in 10 (43%) and 1 (4%) days where as extremely HRF at isolated places in 2 (9%) days, (*v*) Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - responsible for occurrence of HRF at isolated and at a few places in 28 (67%) and 7 (18%) days; for very HRF at isolated and at a few places in 13 (30%) and 2 (5%) day whereas for extremely HRF at isolated in 6 (14%) days, (*vi*) Upper air cyclonic circulation over SHWB-S- responsible for occurrence of HRF at isolated and at a few places in 23 (64%) and 1 (3%) days; very HRF at isolated places in 10 (28%) days where as extremely HRF at isolated places in 2 (6%) days, (*vii*) The monsoon trough or trough of low- responsible for occurrence of HRF at isolated, at a few and at many places respectively in 184 (61%), 80 (26%) and 6 (2%) days; for very HRF at isolated and at a few places respectively in 161 (53%) and 19 (6%) days where as for extremely HRF at isolated and at a few places in 76 (25%) and only 1 (0%) day, (*viii*) North-South trough of low/ trough in monsoon westerlies - responsible for occurrence of HRF at isolated, at a few and at many places respectively in 38 (60%), 5 (8%) and 1 (2%) days; for very HRF at isolated and at a few places respectively in 20 (32%) and 1 (2%) days where as for extremely HRF at isolated places in 5 (8%) days, (*ix*) Low over Jharkhand- contributes HRF at isolated, at a few and at many places in 32 (59%) and 2 (4%) days; very HRF at isolated and at a few places respectively in 11 (20%) and 1 (2%) days where as extremely HRF at isolated places in 4 (7%) days, (*x*) Trough over Gangetic West Bengal - contributes HRF at isolated, at a few and at many places in 89 (58%) and 14 (9%) days; very HRF at isolated and at a few places respectively in 56 (37%) and 3 (2%) days where as extremely HRF at isolated places in 15 (10%) days, (*xi*) Upper air cyclonic circulation over East Uttar Pradesh and adjoining Bihar - responsible for occurrence of HRF at isolated and at a few places in 16 (55%) and 5 (17%) days; very HRF at isolated places in 8 (28%) days where as extremely HRF at isolated places in 1 (3%) day and (*xii*) Low over Gangetic West Bengal - contributes HRF at isolated places in 18 (53%) days; very HRFs at isolated places in 1 (3%) day.

(b) Location wise, impact of most important synoptic systems (with frequencies more than 5) for the occurrence HRF (at least over isolated places) are shown in Tables 5-7.

5. Conclusions

The distribution of HRF Analysis over Teesta catchment and adjoining areas using synoptic analog method for the period 1998 to 2015 are summarized here:

(a) Total seventy one (71) types of synoptic situations have been identified during 1998 to 2015; (b) Out of 2196 days during 1998 to 2015 of monsoon months (June to September), it has been found that over the entire study area, HRF occurred at least at isolated places in 53% cases; at a few places in 9% cases and at many places in 1% cases; (c) In Upper portion of the study area, HRF occurred at least at isolated places in 8% cases and at a few places in 5% cases; (d) In Middle portion, at least at isolated places in 33% cases; at a few places in 14% cases and at many places in 2% cases; (e) In Lower portion, at least at isolated places in 22% cases; at a few places in 13% cases and at many places in 2% cases; (f) Frequency of HRF event is higher over the Middle and Lower Portion as compared to the Upper Portion of the study area. This is due to the fact that most parts of the Middle and Lower Portions are falling in the foothills and windward side of the Himalayas; (g) Frequency of extremely HRF event is highest over the Lower Portion whereas lowest over the Upper Portion of the study area; (h) Most favorable systems for producing HRF events over study are: Upper air cyclonic circulation over Bihar along with trough passing through SHWB-S (94%), Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal (91%), Upper air cyclonic circulation along with trough passing through SHWB-S (90%), Trough over SHWB-S (89%), Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh (74%), Upper air cyclonic circulation over Bihar (73%), North-South trough of low/ trough in monsoon westerlies (70%), Upper air cyclonic circulation over East Uttar Pradesh & adjoining Bihar (70%), Trough over Gangetic West Bengal (67%), Upper air cyclonic circulation over SHWB-S (65%) and Low over Jharkhand (63%); (i) The synoptic situation *viz*., Upper air cyclonic circulation over SHWB-S has the highest impact in producing HRF activities over Upper and Middle Portion where as Upper air cyclonic circulation along with trough passing through SHWB-S has the most significant impact over the Lower Portion of the study area. Presence of these synoptic systems may warrant for issuing HRF warning at a few places in the area and (j) The occurrence of HRFs at a few or many or most places over this area are mainly due to the presence of (*i*) Upper air cyclonic circulation along with trough passing through SHWB-S (*ii*) monsoon trough or trough of low on sea level chart passing through SHWB-S and (*iii*) Upper air cyclonic system over Bihar with trough passing through SHWB-S and. Persistence of these conditions for two or more days may cause disastrous flood situation in this area. On the other hand, the synoptic situations other than trough passing through SHWB & Sikkim may be responsible for occurrence of HRF only at the isolated places for one or two days but may not create flood like situation over this region generally.

Acknowledgement

The authors are thankful to the Director General of Meteorology, India Meteorological Department, New Delhi for his constant encouragement to carry out the work. The authors are also thankful to DDGM, RMC Kolkata and DDGM, RMC Guwahati for their constant support and providing necessary data to carry out the study.

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