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Prediction of monthly summer monsoon rainfall of four meteorological subdivisions in India

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ABSTRACT

Chhattisgarh (CG), Goa and Konkan (G&K), Gangetic West Bengal (GWB) and West Uttar Pradesh (WUP) Meteorological Subdivisions have exhibited significant trends in south-west monsoon rainfall over the period of 100 years. Therefore, monthly summer monsoon rainfall's (MSMR's) prediction is necessary for aforesaid meteorological subdivisions. In the domain of water resources management, monthly rainfall values of monsoon are more effective as compared to total of monsoon rainfall. Thus, current study is performed to assess the hydroclimatic teleconnection (HCT) between MSMR of aforesaid meteorological subdivisions and lagged circulation indices, which will be useful to predict the MSMR of aforesaid meteorological subdivisions few months ahead. Four models are prepared for assessment of aforesaid HCTs having periods of model development as 1950-1999, 1950-1994, 1950-1989, and 1950-1984 with a common testing period of 2000-2014 for each meteorological subdivision. For each model of each subdivision following methodology is adopted. Significant lagged circulation indices (SLCIs) impacting MSMR of given subdivision are identified by using significant linear correlation. Then, multi-collinearity existing among these SLCIs is eliminated to derive significant and independent lagged circulation indices (SILCIs). SILCIs are used in formulation of monthly composite indices

(MCIs) between MSMR and corresponding SILCIs by employing multivariate linear regression. These MCIs are then used for predicting MSMR of given subdivision over a common testing period. SILCIs derived in the current study have shown effect of other indices on MSMR of aforesaid meteorological subdivisions besides ENSO and EQUINOO. Correlation coefficient values for testing period are found to be higher for G&K and GWB Meteorological Subdivisions as compared to other two subdivisions.

Keywords: Hydro-climatic Teleconnection, Monthly Summer Monsoon Rainfall, Meteorological Subdivisions, Chhattisgarh, Goa and Konkan, Gangetic West Bengal, West Uttar Pradesh, Eleven Circulation Indices

1. INTRODUCTION

The assessment of hydro-climatic linkage amongst the various large scale atmospheric circulations and variation of rainfall in space and time is very essential for country's socio-economic benefit (Maity and Kumar, 2006). Hydrologic variates are having a significant association with atmospheric circulation. This association may be mimicked through two approaches: 1) general circulation models (GCMs) simulations and 2) through assessment of statistical association existing amongst the hydrologic variables and atmospheric/oceanic variables from the different parts of the world. The later association is known as hydro-climatic teleconnection (HCT). GCM's potential skill decreases significantly: 1) from continental or hemispheric scale to local sub grid scale, 2) from free tropospheric variables to surface variables, 3) from variables associated with climate such as pressure, wind, humidity etc. to soil moisture, runoff, and precipitation etc. While later mentioned every case in point 3 is more crucial for the hydrologic regime. Hydrologic modeling corresponding to macro scale, dynamic downscaling method and statistical downscaling method of GCM output to regional spatial scale are employed in large extent to narrow down the gap between hydrologic requirements and the ability of GCM. The assumption of statistical invariance is a basic assumption in any type of statistical downscaling technique which is questionable in the context of climate change, while regional climate models (RCMs) still not able to meet hydrologic system scale, so downscaling is still required for the output from RCMs (Maity et al., 2007). Looking to the drawbacks of GCMs and downscaling approaches later approach i.e., assessment of HCT amongst atmospheric circulations and hydrologic variates is better.

Few works were performed outside of India in order to establish HCT between rainfall and circulation indices (Marcella and Eltahir, 2008; Araghinejad and Meidani, 2013; Ionita, 2014). The influence of circulation indices on ISMR was also studied (Berkelhammer et al., 2013; Surendran et al., 2015; Singhania et al., 2018; Srivastava et al., 2019; Yang and Huang, 2021; Athira et al., 2023 etc). Some studies were performed on assessing HCT amongst the rainfall of the basins or State of India and circulation indices (Kashid et al., 2010; Sankaran and Reddy, 2016; Yin et al., 2016). Maity and Kumar (2006) have integrated the information on EQUINOO and ENSO in the form of monthly composite index (MCI). They have investigated hydroclimatic linkage amongst the monthly Indian Summer Monsoon Rainfall and MCI. They have investigated variation of this association in space for India's five different homogeneous monsoon regions.

Maity and Kumar (2007) have investigated the influence of sea surface temperature (SST) on monthly rainfall of Indian subdivisions. They have also studied relative significance of land surface temperature, ocean-land temperature contrast and SST and their alterations from subdivision to subdivision and season to season.

Guhathakurta and Rajeevan (2006) have noticed decreasing and increasing trends in rainfall of different meteorological subdivisions of India at various statistical significance levels over a time period of 100 years. They have found statistically significant declining trend in rainfall of south-west monsoon (SWM) season for Chhattisgarh (CG) Meteorological Subdivision at 99% level of significance. Thus, CG Meteorological Subdivision is considered as one of the study areas in the current study. Statistically significant increasing trends are detected in SWM rainfall of Goa and Konkan (G&K), West Uttar Pradesh (WUP) and Gangetic West Bengal (GWB) Meteorological Subdivisions at 95%, 90% and 90% levels of significance, respectively. Thus, aforesaid meteorological subdivisions having significant increasing trends are also considered as study areas.

In the domain of water resources management, monthly rainfall values are more useful than the total rainfall quantity of monsoon for cropping operations planning, reservoir operations, distribution of water to various users etc. (Maity and Kumar, 2006).

Through the reviewed literature, it was found that, no reviewed study had assessed HCT between monthly summer monsoon rainfall (MSMR) of CG, G&K, WUP and GWB Meteorological Subdivisions and atmospheric/oceanic circulation indices and its temporal variation. Therefore, above-mentioned research gaps are addressed in the current study by: 1) establishing HCT between the MSMR of four meteorological subdivisions mentioned above and eleven circulation indices and 2) assessment of temporal variation in aforesaid HCTs i.e., how significant and independent circulation indices (SILCIs) affecting the given MSMR of four meteorological subdivisions change with different time periods.

2. STUDY AREA AND DATA COLLECTION

2.1.1 Study Area

Nine out of the 36 meteorological sub-divisions are identical to the states after which they are named. These nine meteorological subdivisions include CG Meteorological Subdivision also (Kelkar and Sreejith, 2020). Chhattisgarh State covers an area of approximately 135,192 Km^2. Chhattisgarh is the 9th largest state of India and it has population of around 25.54 million people. Chhattisgarh is also called as 'Rice Bowl of India' because of its high rice production (https://cgstate.gov.in/en, accessed on 06/08/2025).

Total area of G&K Meteorological Subdivision is 34,095 km^2. It consists of 5 rain gauges with average area per rain gauge as 83×83 km^2. It consists of two districts which have areas less than or equal to 5,000 km^2, two districts which have areas ranging from 5,000 to 10,000 km^2, and one district which has an area ranging from 10,000 to 15,000 km^2 (Parthasarathy et al. 1987).

Total area of GWB Meteorological Subdivision is 66,228 km^2. It consists of 11 rain gauges with average area per rain gauge as 78×78 km^2. It consists of five districts which have areas less than or equal to 5,000 km^2, four districts which have areas ranging from 5,000 to 10,000

km^2, and two districts which have areas ranging from 10,000 to 15,000 km^2 (Parthasarathy et al. 1987).

Total area of WUP Meteorological Subdivision is 96,782 km^2. It consists of 19 rain gauges with average area per rain gauge as 71×71 km^2. It consists of 13 districts which have areas less than or equal to 5,000 km^2, 5 districts which have areas ranging from 5,000 to 10,000 km^2, and one district which has an area ranging from 10,000 to 15,000 km^2 (Parthasarathy et al. 1987). Four sub-divisions (CG-27, G&K-23, GWB-6 and WUP -11) considered in the present study are shown in figure 1.

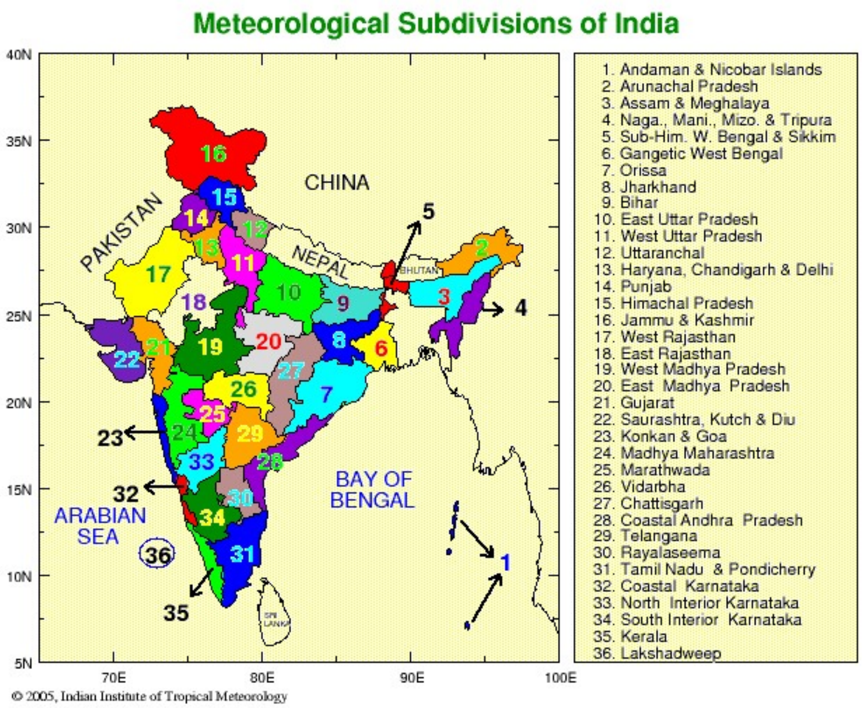

Figure 1 Meteorological subdivisions of India (Source: IITM, Pune)

2.1.2 Data Collection

The summer monsoon rainfall data of CG, G&K, GWB and WUP Meteorological Subdivisions (1871-2016) are acquired from Indian Institute of Tropical Meteorology's (IITM's) website (ftp://www.tropmet.res.in/pub/data/rain/iitm-subdivrf.txt "last accessed on

1/1/2018"). The data utilized in the current study is part of 'IITM Indian regional/sub divisional Monthly Rainfall dataset' (Parthasarathy et al., 1987; Parthasarathy et al.,1993; Mooley et al., 1981; Parthasarathy et al.,1995a; Parthasarathy et al.,1995b; Pant and Kumar, 1997; Kothawale and Rajeevan, 2017). The MSMR data of all four meteorological subdivisions used in the current study corresponds to the period of 1950-2014. The monthly anomaly rainfall data are prepared from monthly rainfall data by using the procedure given in Maity et al. (2007).

The indices employed in the current study are: Arctic oscillation (AO) index, East Atlantic and Western Russia (EAWR) index, East Atlantic (EA) index, El Nino Southern Oscillation (ENSO) index, East Pacific/North Pacific (EPNP) index, Equatorial Zonal Wind Index (EQWIN) index, Pacific/North American Oscillation (PNA) index, Pacific Decadal Oscillation (PDO) index, North Atlantic Oscillation (NAO) index, West Pacific (WP) index and Scandinavia (SCAND) index.

The data of various indices are acquired from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA). Monthly anomaly data of EQWIN index is derived by using the raw data and procedure mentioned in Maity et al. (2007). Monthly anomaly data of ten indices and EQWIN raw data are obtained from the sources given in Table 1 of Singhania et al. (2018).

3. METHODOLOGY

Methodology used in the present study is referred from Singhania et al. (2018). To investigate the temporal variation of HCT present amongst the 11 atmospheric/oceanic circulation indices and MSMR of CG, G&K, GWB and WUP Meteorological Subdivisions, four different models are prepared for each meteorological subdivision with a common testing period of 2000-2014. Four different model development phase periods corresponding to four different models are: Model 1 (1950-1999), Model 2 (1950-1994), Model 3 (1950-1989) and Model 4 (1950-1984). Extensive reduction in the range of continental diurnal temperature was observed from the 1950s, which concur with increase in the quantity of clouds (Hegerl et al., 2007). Therefore, 1950 is considered as the beginning year for each model's development phase period in the current study.

In the current study, four lags i.e., lags 1, 2, 3 and 4 are considered for each circulation index. In each model of each meteorological subdivision, lagged circulation indices (LCIs) having significant correlation (at 5% significance level) with corresponding MSMR are selected as significant LCIs (SLCIs). After determination of SLCIs for MSMR of each model corresponding to each meteorological subdivision, the effect of multi-collinearity present between selected SLCIs is eliminated (if present). If the multicollinearity is exhibited among the two selected SLCIs, then the SLCI having higher value of significant correlation coefficient (CC) with target output (MSMR) is retained and other SLCI is eliminated. After removing the multi-collinearity, significant and independent LCIs (SILCIs) are obtained for each model corresponding to each meteorological subdivision. Then, for each model corresponding to each meteorological subdivision, MCIs are formulated between SILCIs and corresponding observed MSMR by using a multivariate linear regression technique.

A common testing period of 2000-2014 is used for all four models developed for each meteorological subdivision. The MCIs formulated for MSMR are employed to predict corresponding rainfall for common testing period (2000 to 2014) and CC values are estimated between predicted and observed MSMR for each model of each meteorological subdivision.

2. RESULTS of HCT assessment of four meteorological subdivisions

4.1 HCT assessment for CG Meteorological Subdivision

4.1.1 Model development phases for CG Meteorological Subdivision corresponding to four models

4.1.1.1 Selection of SLCIs for CG Meteorological Subdivision for model 1

Based on statistically significant correlation at 5% significance level, SLCIs are selected. The SLCIs selected for the CG Meteorological Subdivision for four months namely June, July, August and September (JJAS) corresponding to model 1 are shown in Table 1. SILCIs obtained after removal of multicollinearity are shown in Table 2.

Table 1 SLCIs selected for MSMR of CG Meteorological Subdivision for the time period (1950-1999) corresponding to model 1

Month	**SLCIs**
June	AO_{MAY}, $EQWIN_{MARCH}$, $EPNP_{MAY}$,
July	$EPNP_{MARCH}$, $EQWIN_{MAY}$
August	AO_{JULY}, WP_{MAY}
September	$EQWIN_{JULY}$, $EQWIN_{MAY}$

4.1.1.2 Formulation of MCIs for MSMR of CG Meteorological Subdivision for model 1

Multicollinearity is exhibited amongst some SLCIs corresponding to three months for model 1 of CG Meteorological Subdivision. The influence of multicollinearity found in aforesaid three months is eliminated by retaining the SLCIs having higher CC with corresponding target outputs correspondent to model 1 of CG Meteorological Subdivision. After that, MCIs are formulated between MSMR of CG Meteorological Subdivision and corresponding SILCIs for model 1 as shown in Table 2. CCs estimated between observed monthly rainfall of the four months i.e., JJAS and corresponding predicted rainfall derived from MCIs are 0.48, 0.32, 0.36 and 0.45, respectively for CG Meteorological Subdivision corresponding to model 1.

Table 2 MCIs formulated for MSMR and CC between observed MSMR and predicted MSMR derived from MCIs corresponding to CG Meteorological Subdivision for model 1 (1950-1999)

Month	**MCI**	**CCs***
June	$RAIN_{JUNE} = 0.08 + 0.47 \times AO_{MAY} - 0.34 \times EQWIN_{MARCH}$	0.48
July	$RAIN_{JULY} = - 0.03 -0.30 \times EPNP_{MARCH}$	0.32
August	$RAIN_{AUGUST} = 0.16 -0.25 \times WP_{MAY} + 0.50 \times AO_{JULY}$	0.36
September	$RAIN_{SEPTEMBER} = - 0.07 + 0.48 \times EQWIN_{JULY}$	0.45

*The significant CC at 5% significance level

4.1.1.3 Formulation of MCIs for CG Meteorological Subdivision for models 2 to 4

Similarly, MCIs are formulated for MSMR of CG Meteorological Subdivision corresponding to models 2, 3 and 4 as shown in table 3.

Table 3 MCIs formulated for MSMR and CC between observed MSMR and predicted MSMR derived from MCIs corresponding to models 2, 3 and 4 for CG Meteorological Subdivision

Month	MCI	CCs*
Model 2 (1950-1994)		
June	$RAIN_{JUNE}$ = - 0.08 + 0.49 x AO_{MAY} - 0.44 x $EPNP_{MAY}$	0.51
July	$RAIN_{JULY}$ = - 0.06 -0.33 x $EPNP_{MARCH}$	0.34
September	$RAIN_{SEPTEMBER}$ = - 0.09 + 0.49 x $EQWIN_{JULY}$	0.47
Model 3 (1950-1989)		
June	$RAIN_{JUNE}$ = - 0.05 -0.42 x $EPNP_{MAY}$ + 0.70 x AO_{MAY}	0.59
July	$RAIN_{JULY}$ = - 0.07 -0.34 x $EPNP_{MARCH}$	0.36
Sept.	$RAIN_{SEPTEMBER}$ = - 0.08 + 0.55 x $EQWIN_{JULY}$	0.53
Model 4 (1950-1984)		
June	$RAIN_{JUNE}$ = - 0.01 +0.72 x AO_{MAY} - 0.37 x $EPNP_{MAY}$	0.60
July	$RAIN_{JULY}$ = 0.11 - 0.30 x $EPNP_{MARCH}$ - 0.27 x $EAWR_{JUNE}$	0.49
August	$RAIN_{AUGUST}$ = 0.31 - 0.36 x WP_{JULY}	0.39
September	$RAIN_{SEPTEMBER}$ = 0.09 + 0.52 x $EQWIN_{JULY}$ - 0.32 x $EAWR_{JUNE}$	0.65

*The significant CC at 5% significance level.

From significant CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models, significant average CCs are estimated for MSMR of CG Meteorological Subdivision and these are shown in Table 4.

Table 4: Significant average CCs estimated amongst the predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models of CG Meteorological Subdivision

Month	**Significant Average CC**
June	0.55
July	0.38
August	0.38
September	0.53

From Table 4, it can be seen that, the significant average CC values are higher corresponding to the rainfall of months June and September, which indicates better predictability of MCIs developed for aforesaid two months.

4.1.1.4 Summary of results corresponding to four model development phase periods for CG Meteorological Subdivision

The HCT between MSMR and SILCIs of CG Meteorological Subdivision and its variation is studied in the current study by developing four models. In Table 2 and 3, MCIs are shown for MSMR of CG Meteorological Subdivision for all four models. SILCIs selected for MSMR of CG Meteorological Subdivision corresponding to four models are shown in Table 5. The SILCIs repeatedly selected for two or more models corresponding to MSMR of CG Meteorological Subdivision are shown in bold font in Table 5.

Table 5 SILCIs selected for formulation of MCIs for MSMR of CG Meteorological Subdivision corresponding to models 1 to 4

Model No. →	**1**	**2**	**3**	**4**
MSMR of CG Meteorological Subdivision ↓	**(1950-1999)**	**(1950-1994)**	**(1950-1989)**	**(1950-1984)**

June	**AO_{MAY}** $EQWIN_{MARCH}$	**AO_{MAY}** **$EPNP_{MAY}$**	**AO_{MAY}** **$EPNP_{MAY}$**	**AO_{MAY}** **$EPNP_{MAY}$**
July	**$EPNP_{MARCH}$**	**$EPNP_{MARCH}$**	**$EPNP_{MARCH}$**	$EAWR_{JUNE}$ **$EPNP_{MARCH}$**
August	WP_{MAY} AO_{JULY}			WP_{JULY}
September	**$EQWIN_{JULY}$**	**$EQWIN_{JULY}$**	**$EQWIN_{JULY}$**	$EAWR_{JUNE}$ **$EQWIN_{JULY}$**

SILCIs selected in two or more modes are called as common SILCIs and SILCIs selected only in one model and not repeated in other modes are called as uncommon FSSIs. The common and uncommon SILCIs among four models developed for MSMR of CG Meteorological Subdivision are as follows. Common indices corresponding to June month rainfall are AO_{MAY}, $EPNP_{MAY}$ while uncommon index is $EQWIN_{MARCH}$. The common index for July month rainfall is $EPNP_{MARCH}$ while uncommon index is $EAWR_{JUNE}$. No common index was found for the August month rainfall while uncommon indices for the same are WP_{MAY}, AO_{JULY} and WP_{JULY}. Common index corresponding to September month rainfall is $EQWIN_{JULY}$ while uncommon index is $EAWR_{JUNE}$.

4.1.2 Testing phase (2000-2014) for CG Meteorological Subdivision corresponding to four models

Regression equations developed in the form of MCIs corresponding to four different models developed for CG Meteorological Subdivision are used for prediction of MSMR for testing period (2000 to 2014). Correlation is found amongst the predicted MSMR by MCIs and respective observed MSMR of CG Meteorological Subdivision corresponding to every model for the duration of 2000-2014 (testing phase) and corresponding CC values are presented in Table 6.

Table 6: CCs estimated between observed MSMR and predicted MSMR derived from MCIs corresponding to four models for testing period (2000-2014) correspondent to CG Meteorological Subdivision

Month ↓	CC Between Observed and Predicted Rainfall for Testing Phase Period (2000-2014)				Average CC for Testing Period
	Model 1	Model 2	Model 3	Model 4	
June	0.18	0.09	0.04	0.02	0.08
July	0.12	0.12	0.12	0.18	0.14
August	-0.05	-	-	0.16	0.06
September	0.18	0.18	0.26	0.07	0.17

Results shown in Table 6 indicate that, average CC values are lower for CG Meteorological Subdivision and hence predictability of formulated MCIs for CG Meteorological Subdivision is found to be less.

4.2 HCT assessment for G&K Meteorological Subdivision

4.2.1 Formulation of MCIs for MSMR of G&K Meteorological Subdivision

SILCIs used in the formulation of MCIs after removal of multicollinearity for all four models corresponding to G&K Meteorological Subdivision are shown in Table 7.

Table 7 MCIs formulated for MSMR and CC between observed MSMR and predicted MSMR derived from MCIs corresponding to models 1 to 4 for G&K Meteorological Subdivision

Model No.	Month	MCI	Correlation Coefficient*
Model 1	July	$RAIN_{JULY} = (0.34) \times EQWIN_{JUNE} + (0.24) \times EPNP_{APRIL} - (0.51) \times AO_{MAY} - 0.02$	0.56

(1950-1999)	August	$RAIN_{AUGUST}$ = (0.16) x PDO_{JUNE} – (0.32) x $EPNP_{JULY}$ – (0.50) x AO_{JUNE} + 0.02	0.53
	September	$RAIN_{SEPTEMBER}$ = (0.20) x $SCAND_{MAY}$ –(0.62) x $ENSO_{AUGUST}$ – 0.18	0.56
Model 2 (1950-1994)	July	$RAIN_{JULY}$ = (0.37) x $EQWIN_{JUNE}$ + (0.27) x $EPNP_{APRIL}$ – (0.54) x AO_{MAY} + 0.005	0.59
	August	$RAIN_{AUGUST}$ = – (0.30) x $EPNP_{JULY}$ + 0.01	0.37
	September	$RAIN_{SEPTEMBER}$ = (0.29) x $SCAND_{MAY}$ – (0.56) x $ENSO_{JUNE}$ – 0.18	0.47
Model 3 (1950-1989)	June	$RAIN_{JUNE}$ = (0.25) x $SCAND_{MARCH}$ – 0.03	0.24
	July	$RAIN_{JULY}$ = (0.26) x $EPNP_{APRIL}$ + 0.06	0.30
	August	$RAIN_{AUGUST}$ = – (0.32) x $EPNP_{JULY}$ + 0.01	0.38
	September	$RAIN_{SEPTEMBER}$ = – (0.66) x $ENSO_{AUGUST}$ – 0.14	0.51
Model 4 (1950-1984)	June	$RAIN_{JUNE}$ = (0.41) x $SCAND_{MARCH}$ – 0.03	0.36
	July	$RAIN_{JULY}$ = (-0.27) x $SCAND_{MARCH}$ + (0.37) x $EQWIN_{MAY}$ + (0.32) x $EPNP_{APRIL}$ + 0.10	0.58
	August	$RAIN_{AUGUST}$ = – (0.41) x $EPNP_{JULY}$ - 0.03	0.52
	September	$RAIN_{SEPTEMBER}$ = – (0.81) x $ENSO_{AUGUST}$ – 0.25	0.58

*The significant CC at 5% significance level.

From significant CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models, significant average CCs are estimated for G&K Meteorological Subdivision and these are shown in Table 8.

Table 8: Significant average CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models for G&K Meteorological Subdivision

Month	**Significant Average CC**
June	0.30
July	0.51

August	0.45
September	0.53

From Table 8, it can be seen that, significant average CC values are higher corresponding to the rainfall of months September and July, which shows better predictability of MCIs developed for aforesaid two months.

4.2.2 Summary of results corresponding to four model development phase periods for the G&K Meteorological Subdivision

The HCT between the MSMR and corresponding SILCIs of G&K Meteorological Subdivision and its variation is assessed in the current study through development of four models. The MCIs formulated for MSMR of G&K Meteorological Subdivision for all four models are shown in Table 7. SILCIs selected for MSMR of G&K Meteorological Subdivision corresponding to four models are shown in Table 9. The SILCIs repeatedly selected in two or more models are shown in bold font in Table 9.

Table 9 SILCIs selected for formulation of MCIs for MSMR of G&K Meteorological Subdivision corresponding to models 1 to 4

Model No. → **MSMR of G&K Meteorological Subdivision ↓**	**1** **(1950-1999)**	**2** **(1950-1994)**	**3** **(1950-1989)**	**4** **(1950-1984)**
June			$\mathbf{SCAND_{MARH}}$	$\mathbf{SCAND_{MARH}}$
July	$\mathbf{EQWIN_{JUNE}}$ $\mathbf{EPNP_{APRIL}}$ $\mathbf{AO_{MAY}}$	$\mathbf{EQWIN_{JUNE}}$ $\mathbf{EPNP_{APRIL}}$ $\mathbf{AO_{MAY}}$	$\mathbf{EPNP_{APRIL}}$	$EQWIN_{MAY}$ $SCAND_{MARCH}$ $\mathbf{EPNP_{APRIL}}$
August	PDO_{JUNE}	$\mathbf{EPNP_{JULY}}$	$\mathbf{EPNP_{JULY}}$	$\mathbf{EPNP_{JULY}}$

	EPNP$_{JULY}$ AO$_{JUNE}$			
September	**SCAND$_{MAY}$** **ENSO$_{AUGUST}$**	**SCAND$_{MAY}$** ENSO$_{JUNE}$	**ENSO$_{AUGUST}$**	**ENSO$_{AUGUST}$**

The common and uncommon indices among four models developed for MSMR of G&K Meteorological Subdivision are as follows. Common index corresponding to June month rainfall is SCAND$_{MARH}$ while there is no uncommon index for the same. The common indices for July month rainfall are EQWIN$_{JUNE,}$ EPNP$_{APRIL}$ and AO$_{MAY}$ while uncommon indices are EQWIN$_{MAY}$ and SCAND$_{MARCH}$. Common index corresponding to August month rainfall is EPNP$_{JULY}$ while uncommon indices for the same are PDO$_{JUNE}$ and AO$_{JUNE}$. Common indices corresponding to September month rainfall are SCAND$_{MAY}$ and ENSO$_{AUGUST}$ while ENSO$_{JUNE}$ is uncommon index.

4.2.3 Testing Phase (2000-2014) for G&K Meteorological Subdivision

Regression equations developed in the form of MCIs for four different models developed corresponding to G&K Meteorological Subdivision are used for prediction of MSMR for testing period (2000 to 2014). Correlation is found amongst the predicted MSMR by MCIs and respective observed MSMR for the duration of 2000-2014 and correspondent values of CC are presented in Table 10.

Table 10: CCs estimated between observed MSMR and predicted MSMR derived from MCIs for four models corresponding to testing period (2000-2014) for G&K Meteorological Subdivision

Month ↓	**Model 1 (1950-1999)**	**Model 2 (1950-1994)**	**Model 3 (1950-1989)**	**Model 4 (1950-1984)**	**Average**
June	-	-	0.31	0.31	0.31
July	0.51	0.51	0.18	0.40	0.40

August	0.15	0.35	0.33	0.33	0.29
September	0.47	0.47	0.15	0.15	0.31

Results shown in Table 10 indicate that, average CC values are moderate but these are higher as compared to that of CG Meteorological Subdivision.

4.3 HCT assessment for GWB Meteorological Subdivision

4.3.1 Formulation of MCIs for MSMR of GWB Meteorological Subdivision

SILCIs used in the formulation of MCIs after removal of multicollinearity for all four models corresponding to GWB Meteorological Subdivision are shown in Table 11.

Table 11 MCIs formulated for MSMR and CC between observed MSMR and predicted MSMR derived from MCIs corresponding to models 1 to 4 for GWB Meteorological Subdivision

Model No.	Month	MCI	Correlation Coefficient*
Model 1 (1950-1999)	June	$RAIN_{JUNE}$ = (-0.41) x WP_{APRIL} – (0.37) x $EQWIN_{MARCH}$ – (0.30) x $EAWR_{MARCH}$ + 0.14	0.68
	July	$RAIN_{JULY}$ = (-0.32) x $SCAND_{MAY}$ - (0.32) x EA_{MAY} - 0.03	0.43
	August	$RAIN_{AUGUST}$ = (-0.26) x $EPNP_{APRIL}$ + (0.27) x $EPNP_{JULY}$ - 0.07	0.47
	September	$RAIN_{SEPTEMBER}$ = (0.28) x NAO_{MAY} + 0.01	0.28
Model 2 (1950-1994)	June	$RAIN_{JUNE}$ = (-0.37) x WP_{APRIL} – (0.43) x $EQWIN_{MARCH}$ + (0.30) x EA_{APRIL} + 0.28	0.65
	July	$RAIN_{JULY}$ = (-0.38) x EA_{MAY} - 0.11	0.38
	August	$RAIN_{AUGUST}$ = (0.25) x $SCAND_{MAY}$ - (0.20) x PNA_{JULY} + (0.26) x $EPNP_{JULY}$ – (0.27) x $EPNP_{APRIL}$ - 0.24	0.62
Model 3	June	$RAIN_{JUNE}$ = (-0.28) x WP_{APRIL} – (0.41) x $EQWIN_{MARCH}$ – (0.25) x $EAWR_{MARCH}$ + (0.28) x EA_{APRIL} + 0.32	0.73

(1950-1989)	July	$RAIN_{JULY} = (-0.32) \text{ x } NAO_{JUNE} - (0.32) \text{ x } EPNP_{APRIL} - 0.12$	0.51
	August	$RAIN_{AUGUST} = (0.27) \text{ x } SCAND_{MAY} + (0.34) \text{ x } EPNP_{JULY} - (0.20) \text{ x } EPNP_{APRIL} - 0.15$	0.61
	September	$RAIN_{SEPTEMBER} = (-0.25) \text{ x } PDO_{AUGUST} + (0.24) \text{ x } NAO_{JUNE} + (0.44) \text{ x } NAO_{MAY} - 0.07$	0.57
Model 4 (1950-1984)	June	$RAIN_{JUNE} = (-0.46) \text{ x } EQWIN_{MARCH} - (0.22) \text{ x } EAWR_{MARCH} + (0.32) \text{ x } EA_{APRIL} + 0.33$	0.67
	July	$RAIN_{JULY} = (-0.32) \text{ x } NAO_{JUNE} - (0.40) \text{ x } EPNP_{APRIL} - 0.13$	0.59
	August	$RAIN_{AUGUST} = (-0.21) \text{ x } WP_{JULY} + (0.46) \text{ x } SCAND_{MAY} + (0.33) \text{ x } EPNP_{JULY} - (0.23) \text{ x } EPNP_{APRIL} - 0.04$	0.74
	September	$RAIN_{SEPTEMBER} = (-0.38) \text{ x } PDO_{AUGUST} + (0.39) \text{ x } NAO_{MAY} - 0.09$	0.54

*The significant CC at 5% significance level.

From significant CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models, significant average CCs are estimated for GWB Meteorological Subdivision and these are shown in Table 12.

Table 12: Significant average CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR derived from MCIs correspondent to four models for GWB Meteorological Subdivision

Month	**Significant Average CC**
June	0.68
July	0.48
August	0.61
September	0.46

From Table 12, it can be seen that, significant average CC values are higher for the rainfall of June and August months, which indicates better predictability of MCIs formulated for these two months.

4.3.2 Summary of results corresponding to four model development phase periods for the GWB Meteorological Subdivision

The HCT between MSMR and SILCIs of GWB Meteorological Subdivision and its variation is studied in the current study by formulating four models. In Table 11, MCIs are shown for all four models corresponding to MSMR of GWB Meteorological Subdivision. SILCIs selected for MSMR of GWB Meteorological Subdivision corresponding to four models are shown in Table 13. The indices repeatedly selected in two or more models are shown in bold font in Table 13.

Table 13 SILCIs selected for formulation of MCIs for MSMR of GWB Meteorological Subdivision for all four models

Model No. → / **MSMR of GWB Meteorological Subdivision ↓**	**Model 1 (1950-1999)**	**Model 2 (1950-1994)**	**Model 3 (1950-1989)**	**Model 4 (1950-1984)**
June	**$EQWIN_{MARCH}$** **WP_{APRIL}** **$EAWR_{MARCH}$**	**$EQWIN_{MARCH}$** **WP_{APRIL}** **EA_{APRIL}**	**$EQWIN_{MARCH}$** **WP_{APRIL}** **$EAWR_{MARCH}$** **EA_{APRIL}**	**$EQWIN_{MARCH}$** **$EAWR_{MARCH}$** **EA_{APRIL}**
July	$SCAND_{MAY}$ **EA_{MAY}**	**EA_{MAY}**	**NAO_{JUNE}** **$EPNP_{APRIL}$**	**NAO_{JUNE}** **$EPNP_{APRIL}$**
August	**$EPNP_{APRIL}$** **$EPNP_{JULY}$**	**$EPNP_{APRIL}$** **$EPNP_{JULY}$**	**$EPNP_{APRIL}$** **$EPNP_{JULY}$**	**$EPNP_{APRIL}$** **$EPNP_{JULY}$**

		$SCAND_{MAY}$ PNA_{JULY}	**$SCAND_{MAY}$**	**$SCAND_{MAY}$** WP_{JULY}
September	**NAO_{MAY}**		**PDO_{AUGUST}** NAO_{JUNE} **NAO_{MAY}**	**PDO_{AUGUST}** **NAO_{MAY}**

The common and uncommon indices among four models developed for MSMR of GWB Meteorological Subdivision are as follows. Common index corresponding to June month rainfall are $EQWIN_{MARCH}$, WP_{APRIL} and $EAWR_{MARCH}$ and EA_{APRIL} while there is no uncommon index for the same. The common indices for July month rainfall are EA_{MAY}, NAO_{JUNE} and $EPNP_{APRIL}$ while uncommon index is $SCAND_{MAY}$. Common indices corresponding to August month rainfall are $EPNP_{APRIL}$, $EPNP_{JULY}$ and $SCAND_{MAY}$ while uncommon indices for the same are PNA_{JULY} and WP_{JULY}. Common indices corresponding to September month rainfall are NAO_{MAY} and PDO_{AUGUST} while NAO_{JUNE} is uncommon index for the same.

4.3.3 Testing Phase (2000-2014) for GWB Meteorological Subdivision

Regression equations developed in the form of MCIs for four different models are employed to predict MSMR of GWB Meteorological Subdivision for testing period (2000-2014). The CCs are estimated amongst the predicted MSMR by MCIs and respective observed MSMR for the duration of 2000-2014 and correspondent values of CCs are presented in Table 14.

Table 14: CCs estimated amongst the observed MSMR and predicted MSMR by MCIs for four models corresponding to testing period (2000-2014) for GWB Meteorological Subdivision

Month ↓	**Model 1 (1950-1999)**	**Model 2 (1950-1994)**	**Model 3 (1950-1989)**	**Model 4 (1950-1984)**	**Average**
June	0.32	0.34	0.32	0.31	0.32

July	0.06	-0.51	0.19	0.20	-0.02
August	0.10	0.22	0.32	0.31	0.24
September	-0.26	-	-0.26	-0.25	-0.26

Results shown in Table 14 indicate that, average CC values are moderate for majority of monsoon months but these are higher as compared to that of CG Meteorological subdivision for majority of monsoon months.

4.4 HCT assessment for WUP Meteorological Subdivision

4.4.1 Formulation of MCIs for MSMR of WUP Meteorological Subdivision

SILCIs used in the formulation of MCIs after the removal of multicollinearity for all four models corresponding to WUP Meteorological Subdivision are shown in Table 15.

Table 15 MCIs formulated for MSMR and CC between observed MSMR and predicted MSMR derived from MCIs corresponding to models 1 to 4 for WUP Meteorological Subdivision

Model No.	Month	MCI	Correlation Coefficient*
Model 1 (1950-1999)	June	$RAIN_{JUNE}$ = (-0.36) x NAO_{APRIL} - (0.27) x $EPNP_{MAY}$ - 0.04	0.47
	August	$RAIN_{AUGUST}$ = (-0.37) x PNA_{MAY} + (0.29) x $EQWIN_{JULY}$ – 0.01	0.44
	September	$RAIN_{SEPTEMBER}$ = (-0.49) x AO_{JUNE} + 0.01	0.29
Model 2 (1950-1994)	June	$RAIN_{JUNE}$ = (-0.33) x NAO_{APRIL} - (0.34) x $EPNP_{MAY}$ - 0.05	0.94
	August	$RAIN_{AUGUST}$ = (-0.29) x PNA_{MAY} + (0.38) x $EQWIN_{JULY}$ – 0.04	0.47
	September	$RAIN_{SEPTEMBER}$ = (0.40) x $EPNP_{MAY}$ – (0.61) x AO_{JUNE} + 0.10	0.50
Model 3	June	$RAIN_{JUNE}$ = (-0.33) x NAO_{APRIL} - (0.34) x $EPNP_{MAY}$ - 0.05	0.49
	July	$RAIN_{JULY}$ = (0.20) x WP_{MARCH} + 0.03	0.18
	August	$RAIN_{AUGUST}$ = (0.42) x $EQWIN_{JULY}$ – 0.08	0.39

(1950-1989)	September	$RAIN_{SEPTEMBER} = (0.35) \times EPNP_{MAY} + (0.25) \times EAWR_{JUNE} - 0.05$	0.44
Model 4 (1950-1984)	June	$RAIN_{JUNE} = (0.18) \times PNA_{APRIL} + (0.30) \times PDO_{FEBURARY} - (0.41) \times EPNP_{MAY} + 0.12$	0.58
	July	$RAIN_{JULY} = (0.21) \times EPNP_{JUNE} + 0.05$	0.35
	August	$RAIN_{AUGUST} = (-0.33) \times PNA_{MAY} + (0.28) \times EQWIN_{JULY} – 0.05$	0.43
	September	$RAIN_{SEPTEMBER} = (0.15) \times EPNP_{MAY} - (0.07) \times EAWR_{JUNE} + 0.08$	0.14

*The significant CC at 5% significance level.

From significant CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models, significant average CCs are estimated for WUP Meteorological Subdivision and these are presented in Table 16.

Table 16: Significant average CCs estimated between predicted MSMR by MCIs and corresponding observed MSMR correspondent to four models for WUP Meteorological Subdivision

Month	**Significant Average CC**
June	0.62
July	0.27
August	0.43
September	0.34

From Table 16, it can be seen that, significant average CC value is more than 0.6 corresponding to June month rainfall, which shows better predictability of MCI developed for June month.

4.4.2 Summary of results corresponding to four model development phase periods for the WUP Meteorological Subdivision

The HCT between MSMR and SILCIs of WUP Meteorological Subdivision and its variation is studied in the current study by formulation of four models. In Table 15, MCIs are shown for all four models corresponding to MSMR of WUP Meteorological Subdivision. SILCIs selected for MSMR of WUP Meteorological Subdivision corresponding to four models are shown in Table 17. The indices repeatedly selected in two or more models are shown in bold font in Table 17.

Table 17 SILCIs selected for formulation of MCIs for MSMR of WUP Meteorological Subdivision for models 1 to 4

Model No. → / **MSMR of WUP Meteorological Subdivision ↓**	**1 (1950-1999)**	**2 (1950-1994)**	**3 (1950-1989)**	**4 (1950-1984)**
June	**NAO_{APRIL}** **$EPNP_{MAY}$**	**NAO_{APRIL}** **$EPNP_{MAY}$**	**NAO_{APRIL}** **$EPNP_{MAY}$**	PNA_{APRIL} **$EPNP_{MAY}$** PDO_{FEB}
July			WP_{MARCH}	$EPNP_{JUNE}$
August	**PNA_{MAY}** **$EQWIN_{JULY}$**	**PNA_{MAY}** **$EQWIN_{JULY}$**	**$EQWIN_{JULY}$**	**$EQWIN_{JULY}$** **PNA_{MAY}**
September	**AO_{JUNE}**	**$EPNP_{MAY}$** **AO_{JUNE}**	**$EPNP_{MAY}$** **$EAWR_{JUNE}$**	**$EPNP_{MAY}$** **$EAWR_{JUNE}$**

The common and uncommon indices among four models developed for MSMR of WUP Meteorological Subdivision are as follows. Common indices corresponding to June month rainfall are NAO_{APRIL} and $EPNP_{MAY}$ while uncommon indices for the same are PNA_{APRIL} and

PDO_{FEB}. No common index is found for July month rainfall while uncommon indices for the same are WP_{MARCH} and $EPNP_{JUNE}$. Common indices corresponding to August month rainfall are PNA_{MAY} and $EQWIN_{JULY}$ while there is no uncommon index found for the same. Common indices corresponding to September month rainfall are AO_{JUNE}, $EPNP_{MAY}$ and $EAWR_{JUNE}$ while there is no uncommon index for the same.

4.4.3 Testing Phase (2000-2014) for WUP Meteorological Subdivision

Regression equations developed in the form of MCIs for four different models are employed for prediction of MSMR of WUP Meteorological Subdivision for testing period (2000 to 2014). CCs are estimated amongst the predicted MSMR by MCIs and respective observed MSMR for the duration of 2000-2014 and correspondent CC values are presented in Table 18.

Table 18: CCs estimated between observed MSMR and predicted MSMR by MCIs for four models corresponding to WUP Meteorological Subdivision

Months ↓	**Model 1 (1950-1999)**	**Model 2 (1950-1994)**	**Model 3 (1950-1989)**	**Model 4 (1950-1984)**	**Average**
June	0.19	0.21	0.21	-0.02	0.15
July	-	-	-0.05	0.03	-0.01
August	0.04	0.03	-0.03	0.04	0.02
September	0.19	0.20	0.27	0.02	0.17

Results shown in Table 18 indicate that, average CC values are lower for WUP Meteorological Subdivision and hence predictability of formulated MCIs for WUP Meteorological Subdivision is found to be less.

3. CONCLUSIONS

In this study, HCT between the MSMR of four meteorological subdivisions and SILCIs and its variation (wherever present) are assessed in the present study by formulating four different models and common testing period. Aforementioned HCT assessments shown that, SILCIs selected for MSMR of four meteorological subdivisions corresponding to different models (having different time periods) are varying in majority of the cases which clearly emphasized on the point that aforesaid HCTs have shown temporal variations. Also, SILCIs derived in the current study have shown effect of other indices on MSMR of aforesaid meteorological subdivisions besides ENSO and EQUINOO. CC values for testing period are found to be higher for G&K and GWB Meteorological Subdivisions as compared to other two meteorological subdivisions. The performance of G&K Meteorological Subdivision is found to be best among all four meteorological subdivisions. Average CCs estimated between observed MSMR and predicted MSMR of June, July, August and September for four models corresponding to testing period (2000-2014) for G&K Meteorological Subdivision are 0.31, 0.40, 0.29 and 0.31, respectively. The formulated MCIs for MSMR of G&K and GWB Meteorological Subdivisions which have shown good predictability can be used for prediction of corresponding MSMR few months ahead. The limitations of the present study are use of eleven circulation indices as input and use of multivariate linear regression (linear technique) for assessment of HCT. Future study may be carried out by using more than eleven circulation indices as input and by using non-linear technique for assessment of HCT.

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