Seasonal Prediction of Indian Monsoons

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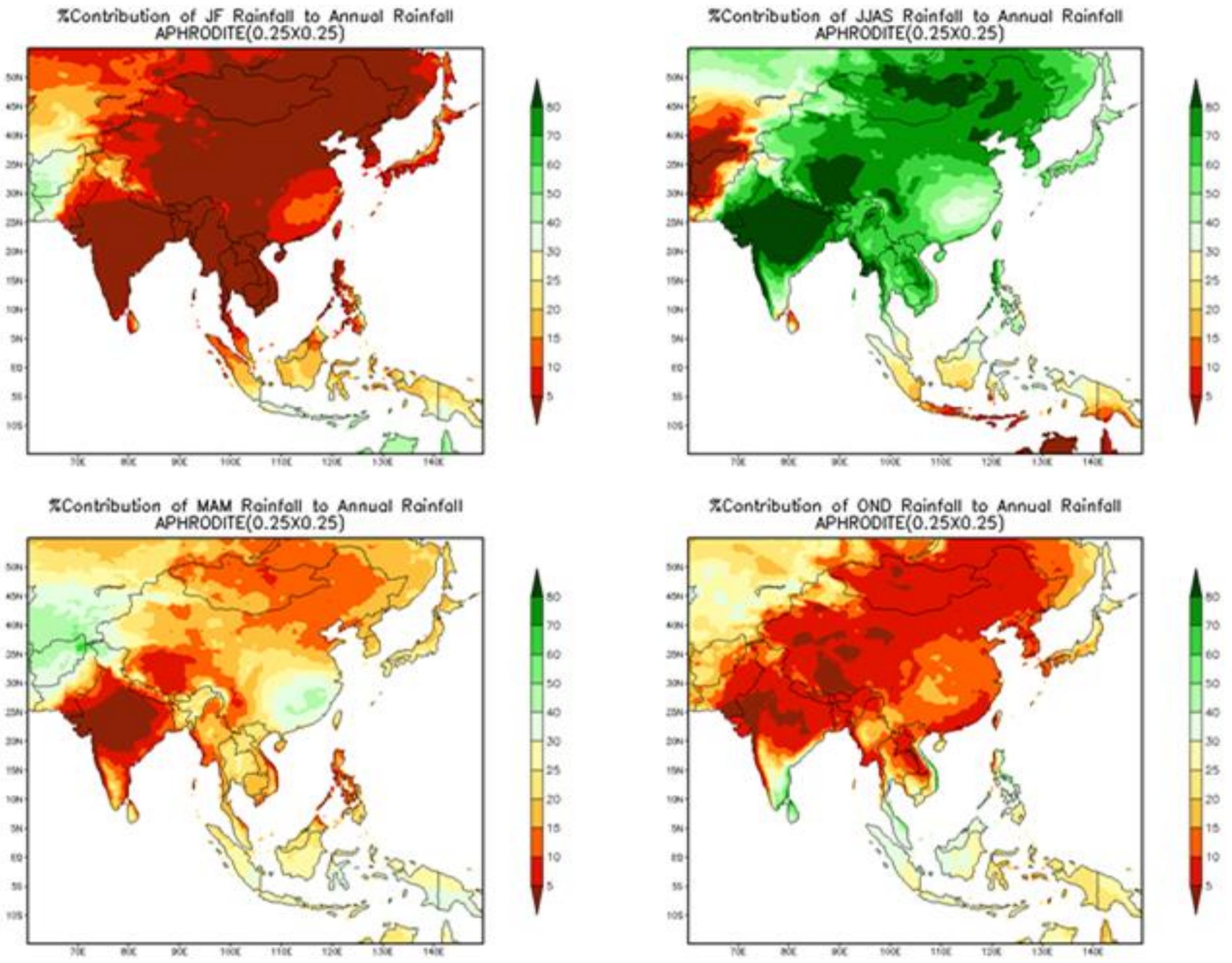
Contribution of Seasonal Rainfall to the Annual Rainfall

Winter

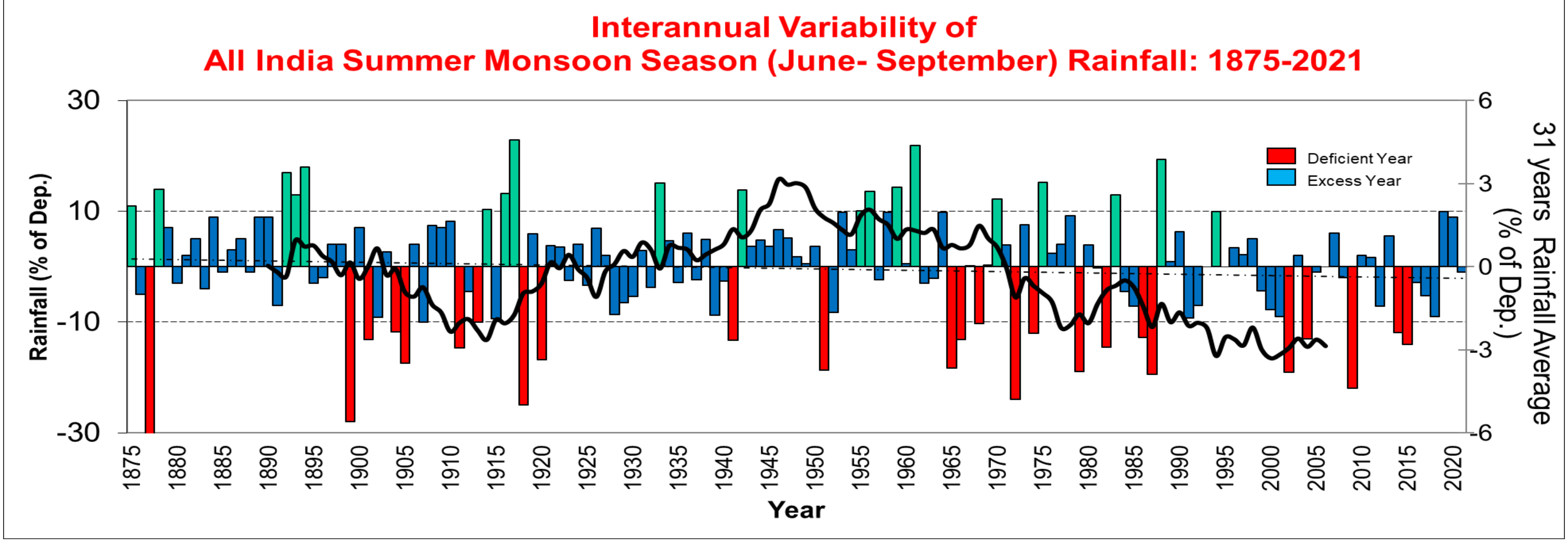
Southwest Monsoon Season
(June to September)



Pre-Monsoon

Northeast Monsoon Season
(October to December)

The monsoons (both Southwest and northeast) dominate the annual cycle of rainfall in India, which has strong influence on the agricultural practices in the country. Among the two monsoons, the southwest monsoon experienced from June to September is the principal rainy season for most parts of the country with a contribution of more than 75% of the annual rainfall. The NE monsoon rainfall is experienced during October to December period provides rainfall mainly over south Peninsula.

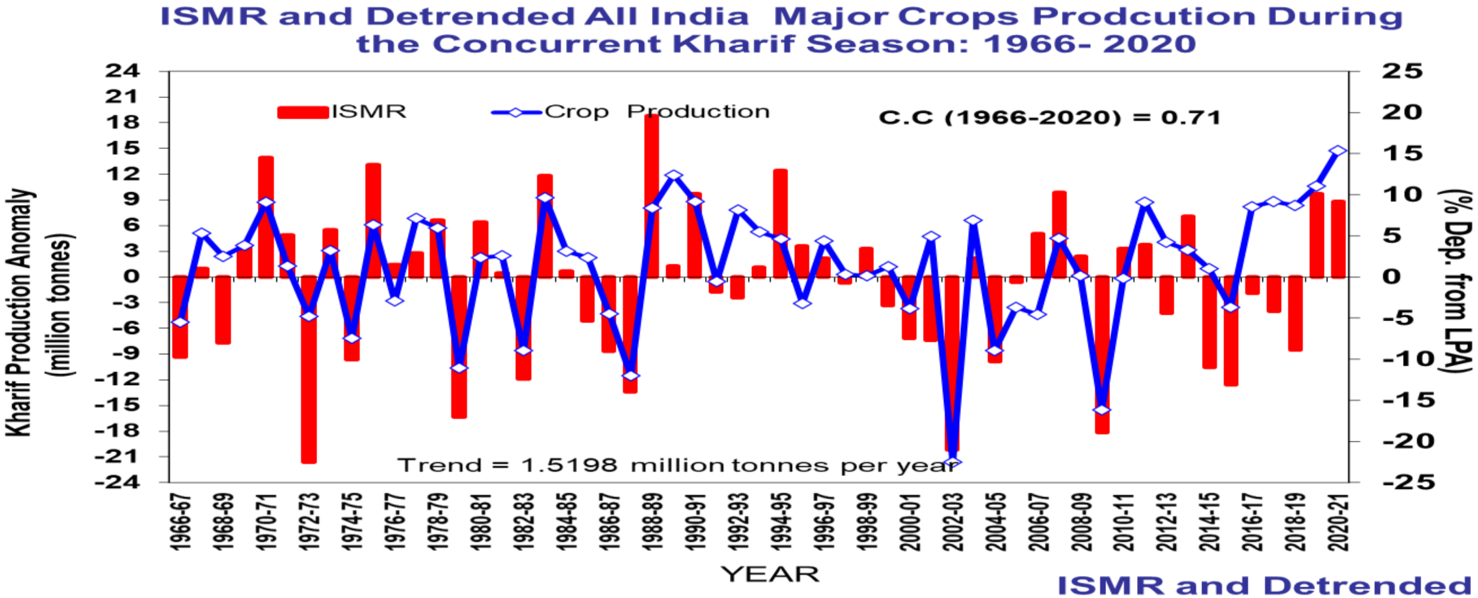


- **An important feature of the southwest monsoon is its stability and regularity**
- **India southwest monsoon season rainfall (ISMR) is within ±30% of its long period average (LPA) during almost all years**
- **ISMR within ±10% of LPA in about 70% of the years.**
- **However variability of monsoon rainfall at regional scale is more than this.**

Deficient years = 25 years (17%) Excess years = 19 Years (13%)

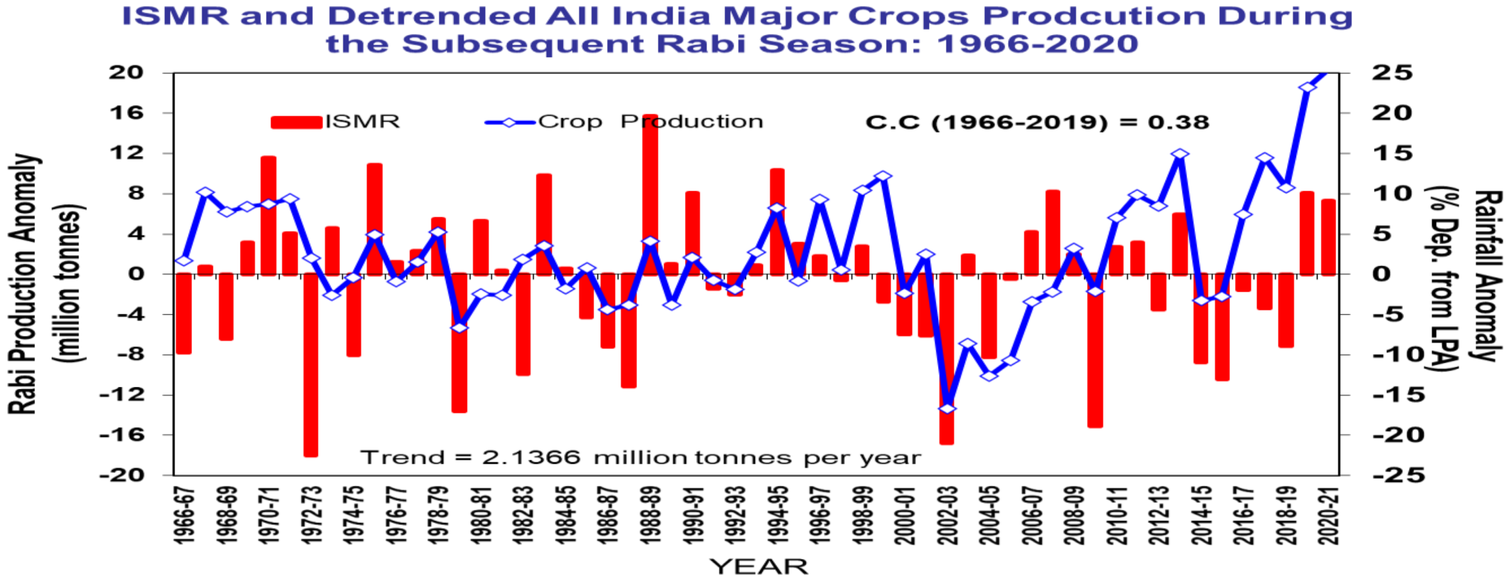
- Slight decreasing trend (insignificant)
- Passing through a below normal epochal variation as indicated by the 31 years moving average
- Since 2001, 13 below LPA years with 5 in deficient category
- 1994 was the last excess year

SW Monsoon Rainfall Vs Major Crops Production



Crop production deviation for any year is a measure of the impact of the monsoon rainfall of that year. The above figures indicate strong positive correlation of all India summer monsoon rainfall with Kharif & Rabbi crop production

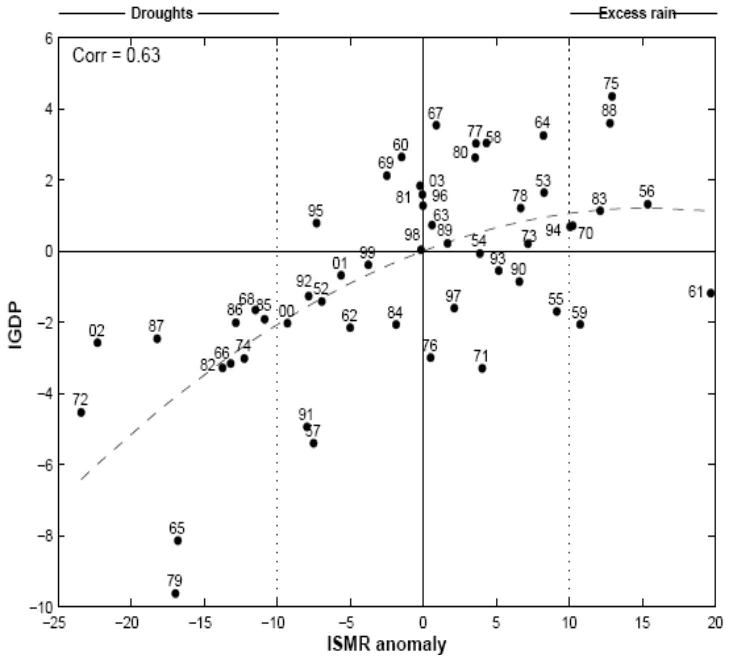
Any significant changes in the temporal and spatial distribution of the rainfall has noticeable impact on the country's agriculture production.



Although the year-to-year variation of seasonal mean all India rainfall (ISMR) is only about 10% of the mean (88 cm), it has strong link with the country's food production.

Indian Monsoon & Economics

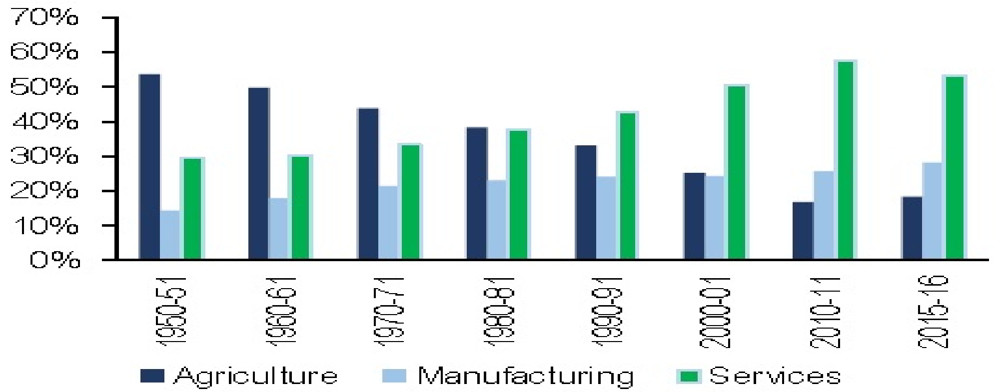
Impact of a severe drought on GDP remains 2 to 5% throughout, despite the substantial decrease in the contribution of agriculture to GDP over the five decades (**Gadgil and Gadgil 2006)**



Labour force by occupation

agriculture: 47%,
industry: 22%,
services: 31%
(2014 est.)

Contribution to GDP of sectors (%)



Sources: Ministry of Statistics and Programme Implementation; PRS.

Performance of ISMR also has significant influence on the Indian Gross Domestic Product (IGDP) (Gadgil and Gadgil, 2006). Hence, predicting the seasonal mean ISM rainfall is of great socio-economic importance for the country.

Various Approaches used for the Seasonal Forecasting of Indian Monsoon

- **Empirical/ Statistical model**
  - Multiple Regression
  - Canonical Correlation Analysis
  - Artificial Neural Network
  - Discriminant Analysis
  - Ex: IMD Operational LRF till 2020

– based on historical observed data for the predictand (e.g. rainfall, temperature) and for relevant predictors (e.g. SST, Snow Cover, Surface air temperature etc.)

- **Dynamical/ Numerical Model**
  - SST Forced Atmospheric General Circulation models (AGCMs)
  - Ex: IMD SFM (experimental)
  - Coupled General Circulation Models (CGCMs)
  - Ex: IITM CFS

– using prognostic physical equations

2-tiered systems (first predict SST, then climate).

1-tiered systems (predict ocean and atmosphere together)

- **Hybrid Model (Statistical + Dynamical)**
  - Statistical rescaling of dynamical model simulations
  - Ex. IITD – ERPS
  - Multi-Model Ensemble Forecasting
  - Ex: IMD's Current MME Forecasting System

History of Seasonal Prediction In India:
Impact of Monsoon Failure

Indian famine victims following failure of 1877/78 monsoon

Source: British Library

Modern research on climate prediction began as a result of the El Niño event of 1877/78, with its severe impacts on India and North China

History of Seasonal Prediction In India:

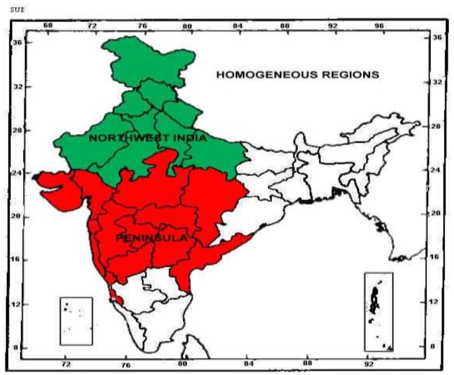
- **H. F. Blandford (1884) - tentative forecasts (1882-1885) based on relationship between winter & spring snow falls over Himalayas and monsoon rainfall.**
- **First operational forecast in 1886 for the whole India (including Burma) on 4th June 1886.**
- **In 1892, LRF for the rainfall for the second half of the monsoon season (August-September) started.**
- **In December 1893, the first forecast for winter precipitation over the Northern and central India was issued.**
- **John Eliot used extra- Indian factors, viz., and pressure of Mauritus, Zanzibar and Seychelles in the monsoon forecast of 1896.**
- **Walker (1904-24) Introduced concept of correlation for LRF. Operational forecast in 1909 was based on regression.**
- **Developed one regression equation each for the monsoon season (Jun-Sept) for all the 3 sub-regions and rainfall of the second half of monsoon season (August and September) over Peninsula and NW India. These 5 equations formed basis for the operational LRF in India till 1987.**
- **1924 to 1987, operational forecasts were issued for NW India and Peninsular India using regression models, which were updated as and when required.**

Traditionally IMD has been using indigenously developed Statistical Models for operational seasonal forecasts of Indian monsoons.

Walker (1904-24)

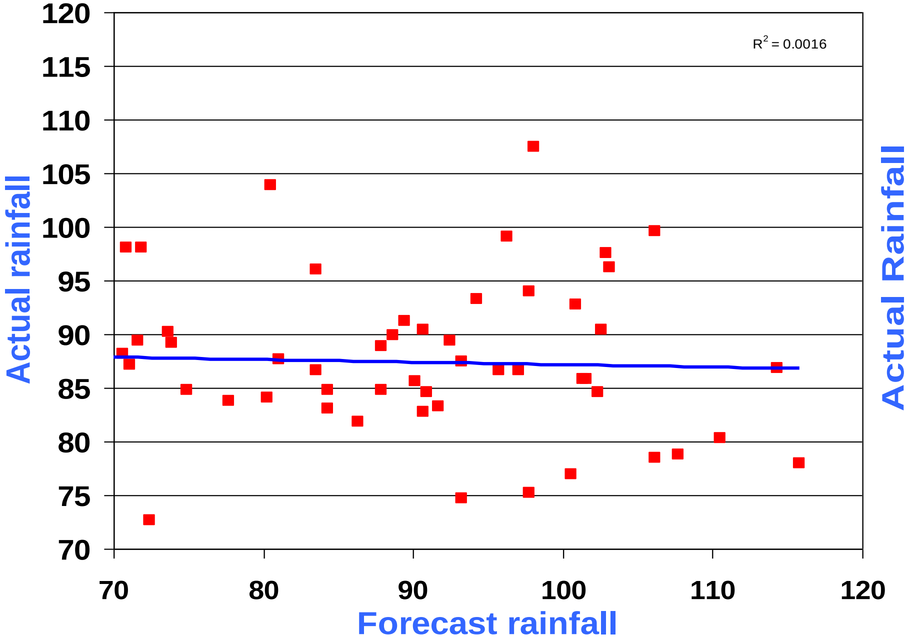
- Over the years, the operational LRF system in India underwent many changes in its approach and scope.

Performance of Empirical Seasonal Forecast of SW Monsoon Rainfall over India: 1932-1987

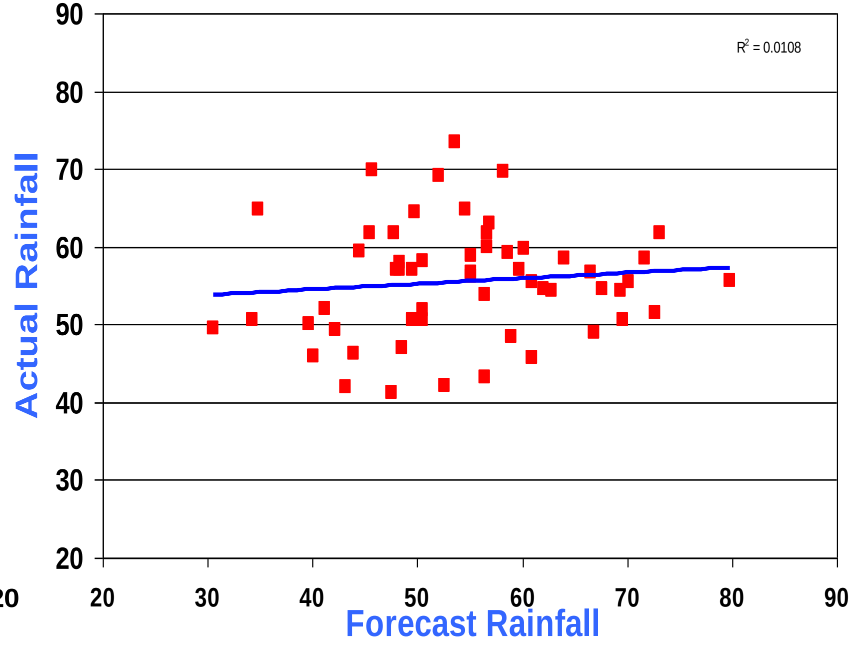


Walker's Homogenous Regions

Peninsula:
Forecast vs Actual rainfall in cm: 1932-1987

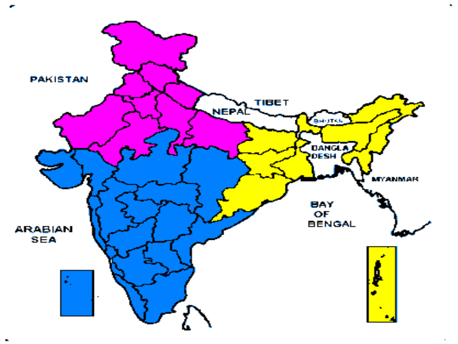


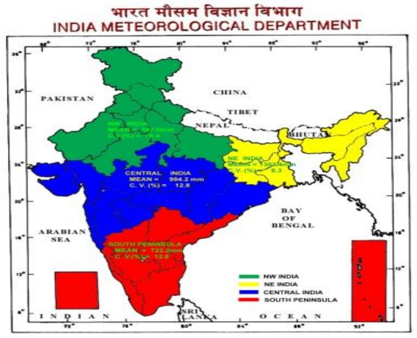
NW India:
Forecast and Actual in cm: 1932-1987



Introduction of New Statistical Models: 1988-2010

- **IN 1988, IMD introduced 16-parameter parametric and power regression models (Gowariker et al. 1989 & 1991) model for the operational forecast for the country as whole. In 2000, model was updated by replacing four predictors. These models were in place till 2002.**
- **In 1999, IMD reintroduced operational forecasts for 3 homogeneous regions of the country (NW India, NE India and Peninsula).**
- **In 2003, two stage forecasting system was introduced. 8/10 Parameters Models were introduced (Rajeevan et al. 2004).**
- **In 2004, the country was divided into 4 homogeneous regions (NW India, Central India, NE India and South Peninsula). Forecast for July rainfall over the country was introduced.**
- **In 2007, new statistical forecasting based on ensemble average introduced (Rajeevan et al. 2007).**
- **In 2009, Forecast for August Rainfall was introduced**
- **In 2010, forecasts for the rainfall during second half of the monsoon season and that during September over the country as a whole were introduced.**

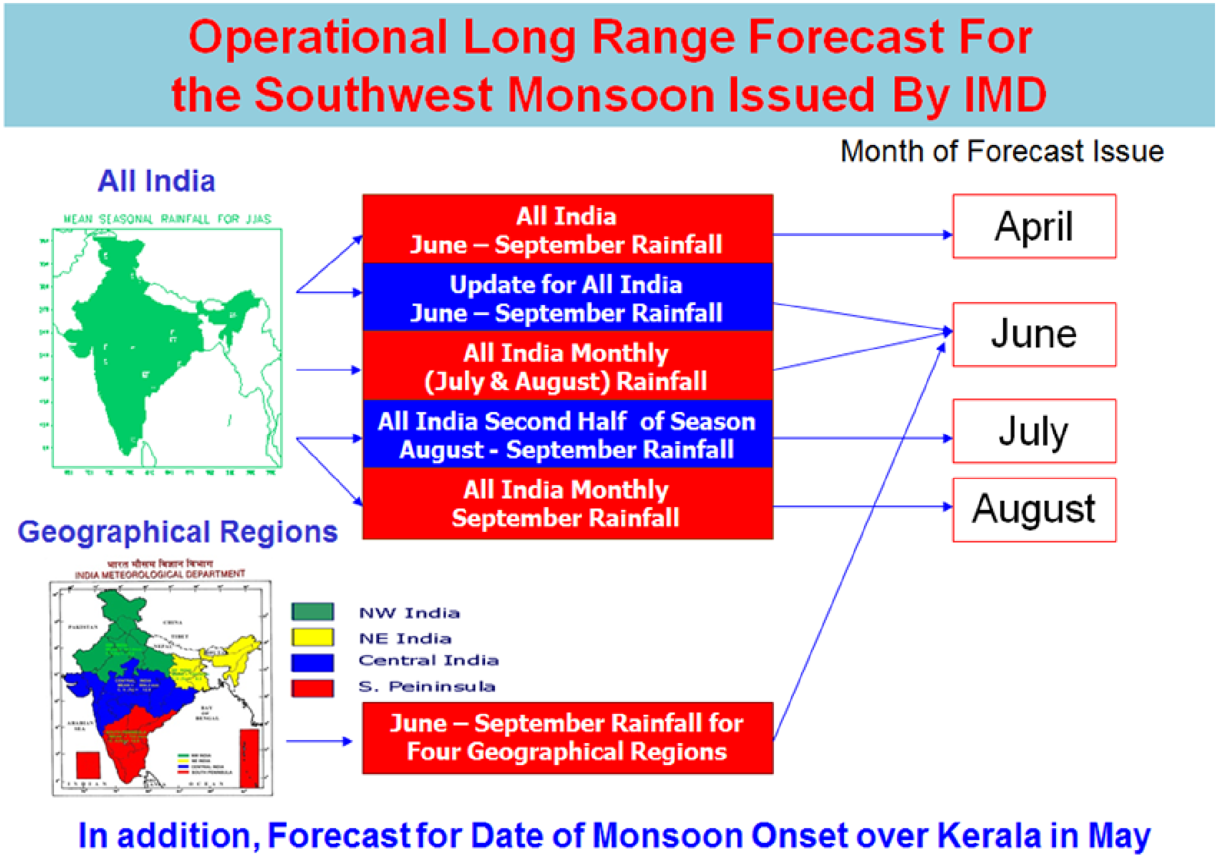




Use of Dynamical Models for the Seasonal Forecasting of Indian Monsoons: 2004-2001

- In 2004, IMD implemented experimental dynamical forecasting system for the southwest monsoon rainfall using the seasonal forecast model (SFM) of the Experimental Climate Prediction Center (ECPC), USA. But the skill of these experimental forecasts based on SFM was very limited.
- In 2012, coupled forecasting system (CFS) was implemented at IITM, Pune on research model under monsoon mission.
- In January 2015, the SFM model was used to generate seasonal forecast outlook for south Asia under WMO Regional Climate Center (RCC)
- In 2016, monsoon mission CFS (MMCFS) model was used to generate ENSO & IOD bulletin and replace SFM to prepare seasonal forecast outlook for south Asia.
- In 2016, MMCFS was started to use to issue Temperature Forecast Outlook for AMJ season for the first time. Temperature forecast outlook for DJF was started in 2016 and that for MAM in 2017.
- In 2017, The high resolution (T382L64) monsoon mission CFS (MMCFS) was transferred to IMD, Pune.
- From 2017, IMD started to use MMCFS to generate experimental forecast for monsoon season along with SEFS
- In 2021 IMD implemented MME methodology based on coupled models

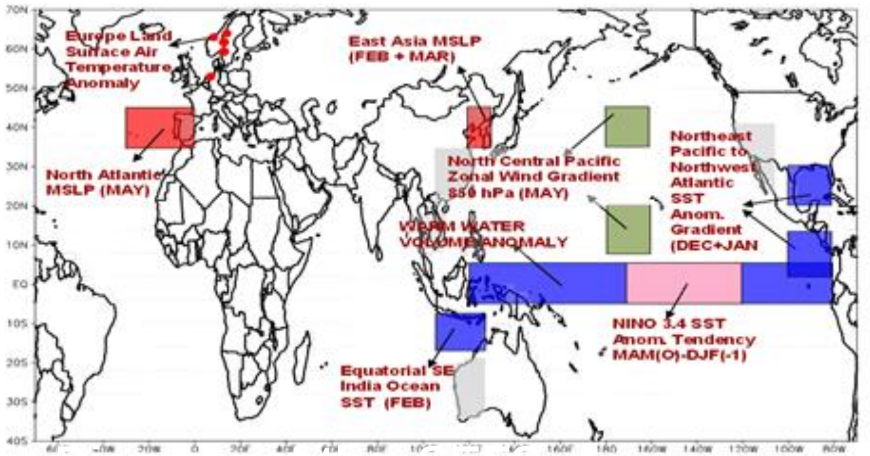
IMD’s Seasonal Forecasting System Based on Statistical Model: 2007- 2020



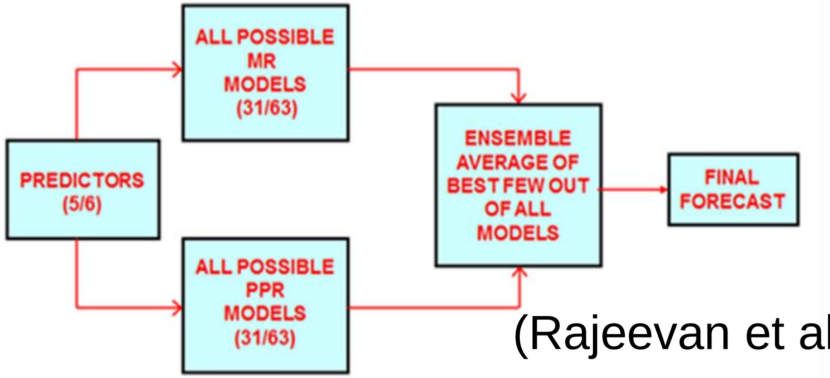
Forecast Period	Forecast Region	Model (Training Window Period)	CC. Actual Vs Forecast Rainfall (Period)	Root Mean Square Error (RMSE) in % of LPA (Period)
June to September	All India	5-P Statistical Ensemble Forecast System (SEFS) (23 yrs)	0.70 (1982-2017)	6.5 (1982-2017)
June to September	All India	6-P (SEFS) (23 yrs)	0.71 (1982-2017)	6.4 (1982-2017)
July	All India	6 –P Principal Component Regression (PCR) (23 yrs)	0.65 (1982-2017)	10.70 (1982-2017)
August	All India	5-P PCR (23 yrs)	0.25 (1999-2017)	11.12 (1999-2017)
September	All India	5-P PCR (23 yrs)	0.69 (1982-2017)	15.76 (1982-2017)
August-September	All India	5-P PCR (23 yrs)	0.48 (1982-2017)	11.93 (1982-2017)
June to September	Northwest India	5-P PCR (30 yrs)	0.61 (1988-2017)	12.37 (1988-2017)
June to September	Northeast India	5-P PCR (30 yrs)	0.54(1988-2017)	10.62 (1988-2017)
June to September	Central India	5-P PCR (30 yrs)	0.36 (1988-2017)	11.63 (1988-2017)
June to September	South Peninsula	6-P PCR (30 yrs)	0.47 (1988-2017)	13.47 (1989-2017)

Statistical Ensemble Forecasting System (SEFS) for Seasonal Rainfall over Country as a whole: 2007-2020

S.No	Predictor Used	Issued in
1	Europe Land Surface Air Temperature Anomaly (January)	April
2	Equatorial Pacific Warm Water Volume (February + March)	April
3	SST Gradient Between Northeast Pacific and Northwest Atlantic (December +January)	April and June
4	Equatorial SE Indian Ocean SST (February)	April and June
5	East Asia Mean Sea Level Pressure (February + March)	April and June
6	Nino 3.4 Sea Surface Temp (MAM + Tendency (MAM-DJF))	June
7	North Atlantic Mean Sea Level Pressure (May)	June
8	North Central Pacific Zonal Wind Gradient 850 hPa (May)	June



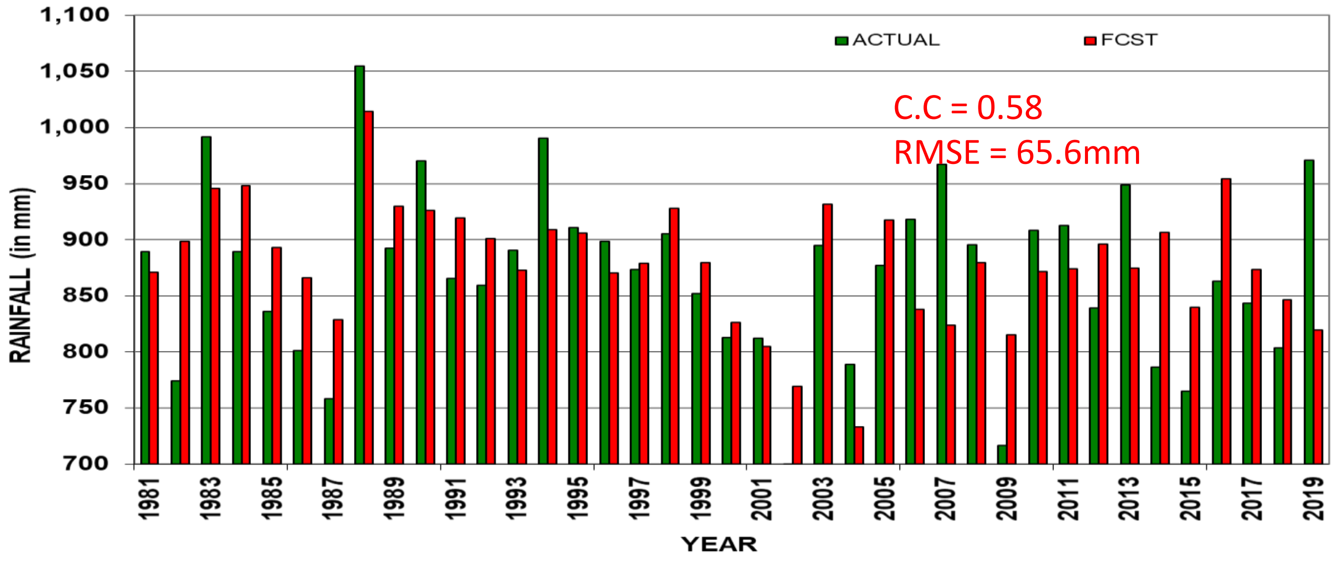
Schematic Diagram of the SEFS



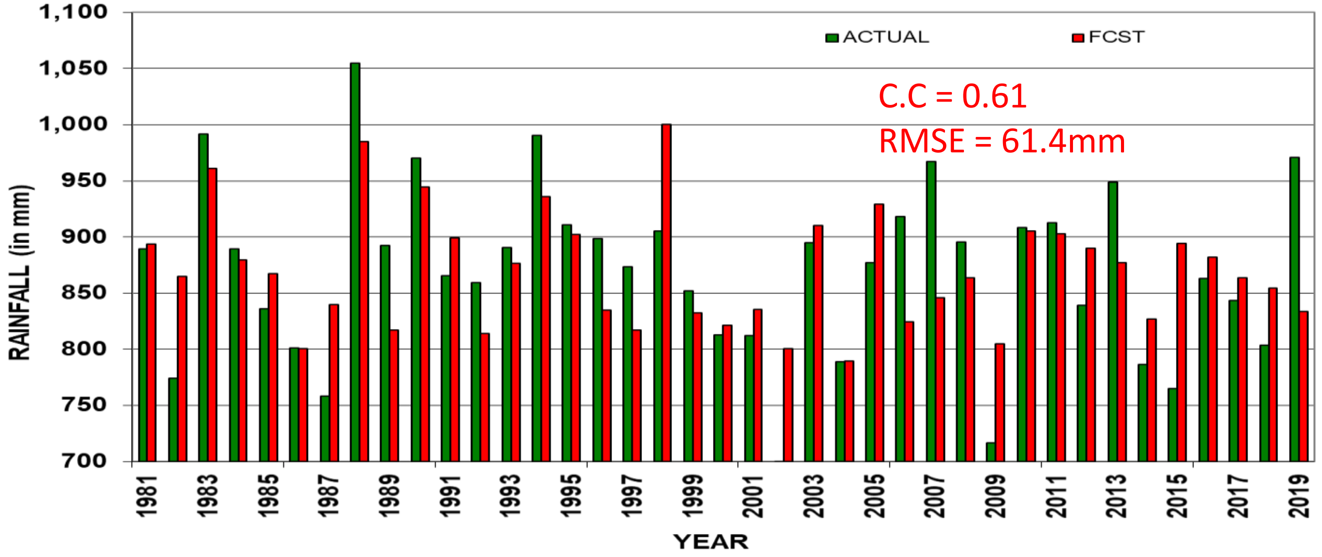
(Rajeevan et al. 2007)

The average of the ensemble forecasts from best out of all possible MR (multiple regression) and PPR (projection pursuit regression) models gives the final forecast.

PERFORMANCE OF ENSEMBLE FORECAST SYSTEM (1981-2019): April



PERFORMANCE OF ENSEMBLE FORECAST SYSTEM (1981-2019): June



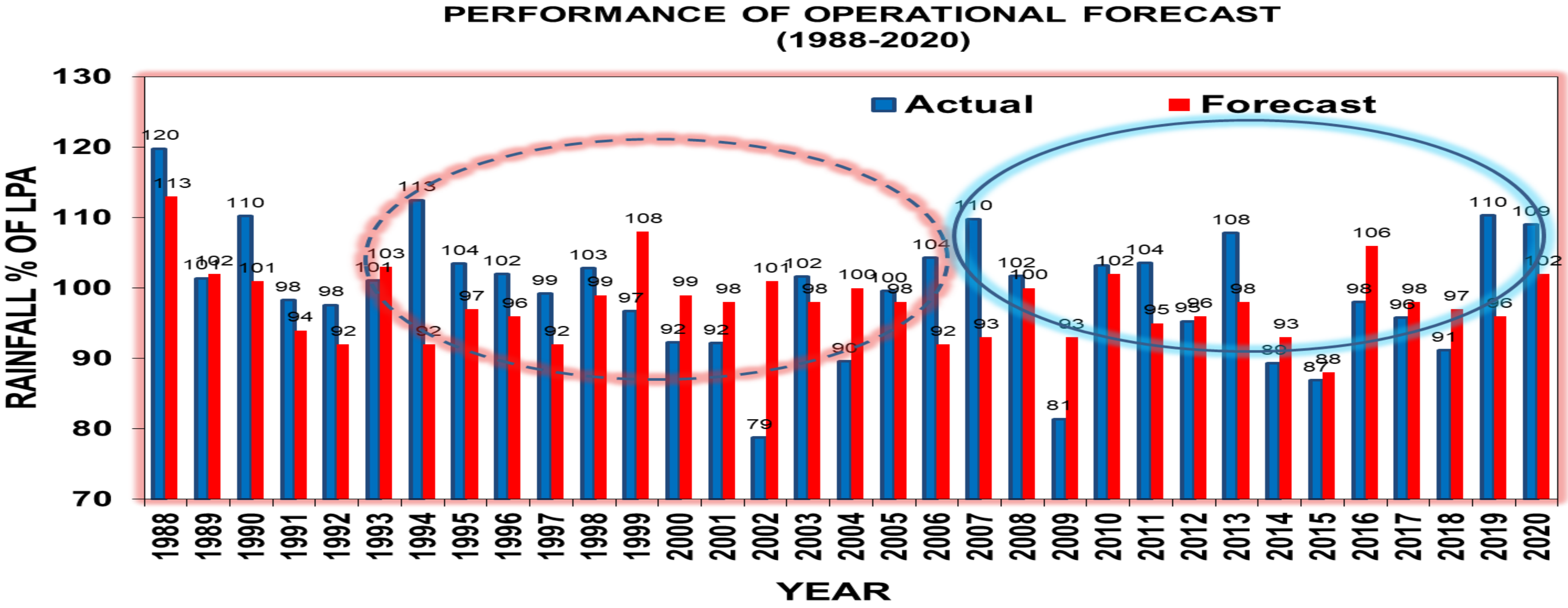
Forecast for all India Seasonal Rainfall during 2020

Region	Forecast (% of LPA)		Actual Rainfall
	15thApril	1st June	(% of LPA)
All India	100± 5	102± 4	109

Probability forecasts for All India Seasonal Rainfall

Category	Rainfall Range (% of LPA)	FCST Prob. April (%)	FCST Prob. June (%)	Clim. Prob (%)
Deficient	< 90%	9	5	16
Below Normal	90-96%	20	15	17
Normal	96%-104%	41	41	33
Above Normal	104%-110%	21	25	16
Excess	> 110%	9	14	17

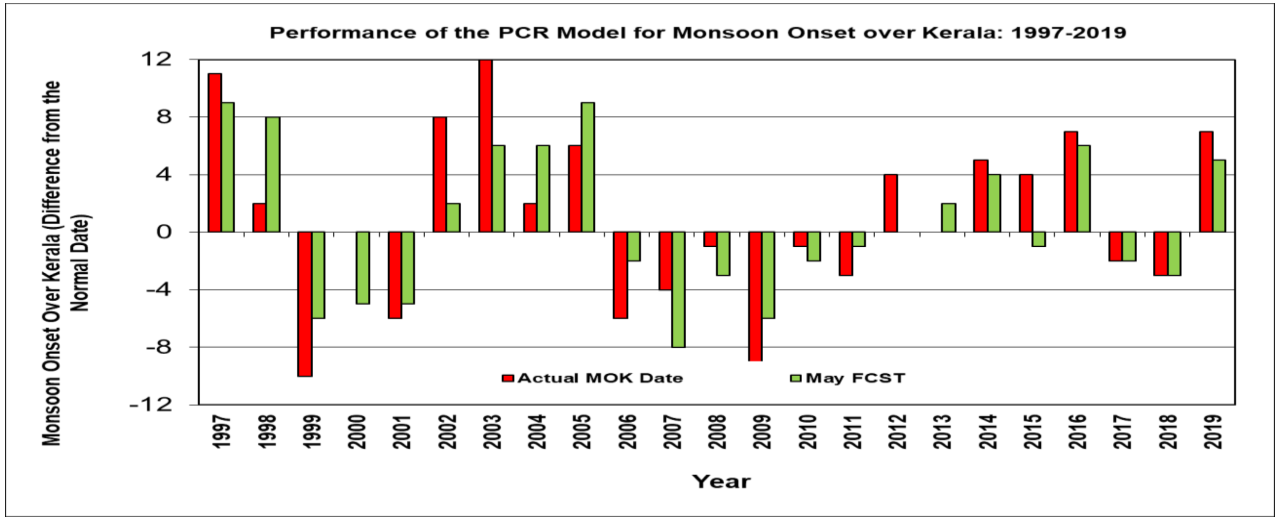
Comparison of Operational Forecast for All India Seasonal Rainfall: (1993-2006) Vs (2007 – 2020)



- Error ≥ 10% in 8 years with highest in 2002 (22.5%) followed by 1994 (20.5%) followed by
- Avg. absolute error during the last 14 years (2007-2020) was 6.6% of LPA compared to that of 7.7% of LPA during the 14 years (1993-2006) just prior to that period.
- C.C between the actual and forecast rainfall for (2007-2020) & (1993-2006) are **0.42 & -0.47** respectively.
- During 1993-2006, the forecast within the ±4% of actual values during 4 years and that during 2007-2020, was during 6 years. *These clearly indicate improvement made in the operational forecast system in the recent 14 years period compared to earlier 14 years period.*

PCR model for the Forecasting date of Monsoon onset over Kerala

No	Name of Predictor	Period	C.C (1975-2000)
1	Zonal Wind at 200hpa over Indonesian region	16th -30th Apr	0.48
2	OLR Over South China Sea	16th- 30thApr	0.40
3	Pre-Monsoon Rainfall Peak Date	Pre-monsoon April-May	0.48
4	Minimum Surface air Tem. over NW India	1st -15th May	-0.37
5	Zonal Wind at 925hpa over Equatorial South Indian Ocean	1st -15th May	0.52
6	OLR Over Southwest Pacific	1st -15th May	-0.53



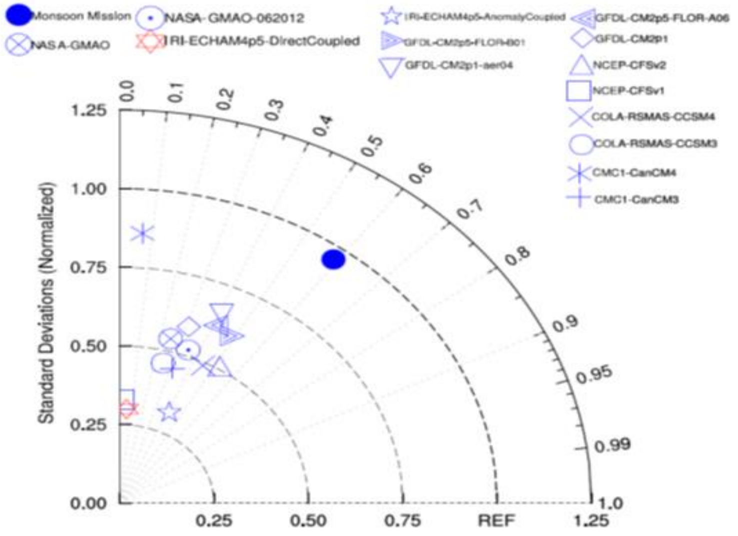
Model error = 4 days

Year	Actual Onset Date	May Forecast Onset Date
2005	7th June	10th June
2006	26th May	30th May
2007	28th May	24th May
2008	31st May	29th May
2009	23rd May	26th May
2010	31st May	30th May
2011	29th May	31st May
2012	5th June	1st June
2013	1st June	3rd June
2014	6th June	5th June
2015	5th June	31st May
2016	8th June	7th June
2017	30th May	30th May
2018	29th May	29th May
2019	8th June	6th June
2020	1st June	5th June
2021	3rd June	31st May

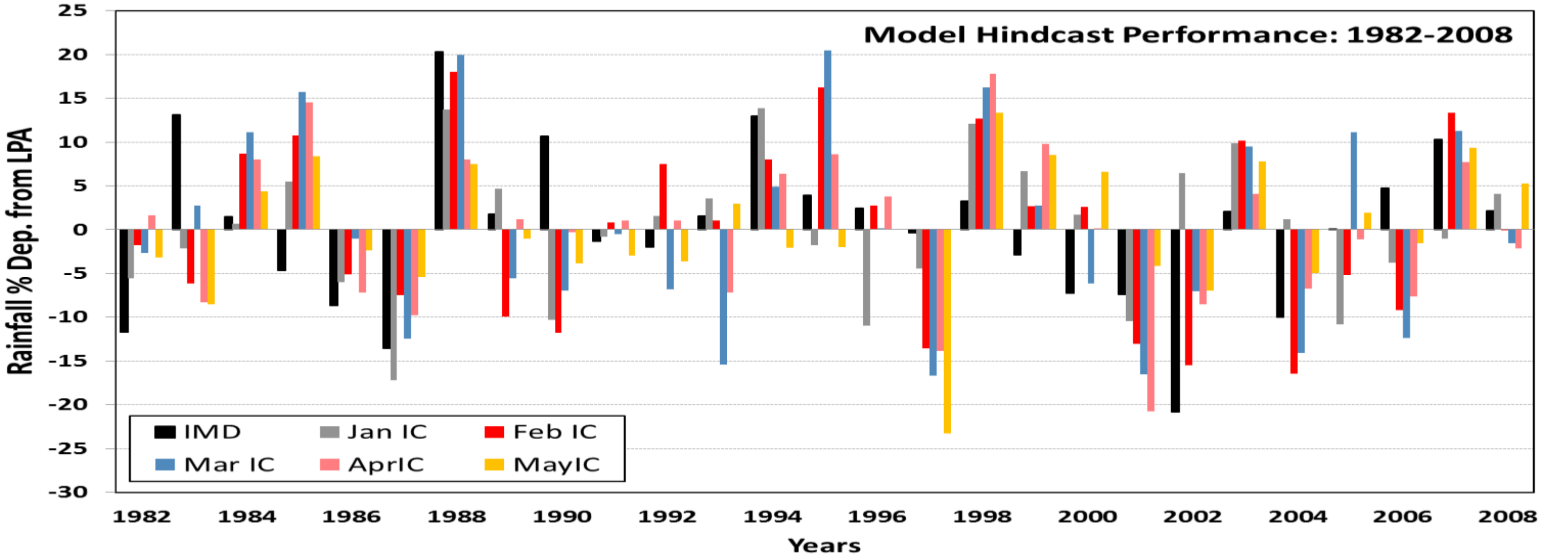
During the last 16 years (2005-2021), the forecast issued for the date of monsoon onset over Kerala was within the forecast limits for all the years except 2015.

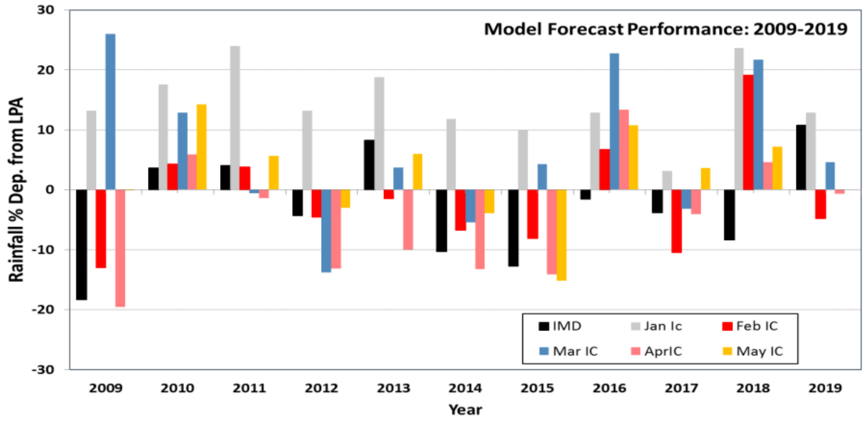
The Monsoon Mission Experimental Dynamical Model Forecasting System

- Under Monsoon Mission, the state-of-the-art Coupled Forecasting System (**MMCFS**) developed by NCEP, USA was implemented in 2012 at the ESSO-IITM, Pune. The model resolution was 100km.
- In 2016, IITM, Pune developed a new version at a higher resolution (38Km) and IMD started to prepare experimental forecasts for Monsoon rainfall.
- In the same year, IMD started to you the model outputs for generating operational subdivision wise temperature forecast.
- The latest high resolution research version of the MMCFS was implemented at IMD, Pune in 2017.
- The model shows a moderate skill for both temperature and rainfall forecast.
- The rainfall forecast from MMCFS was used as an additional input to operational forecast from 2012.



Among the various global coupled model, MMCFS showed highest skill.





During 7 (6) years of the period 2009-2019, the Feb (March) IC based forecast was able to indicate correct sign of the observed rainfall anomaly

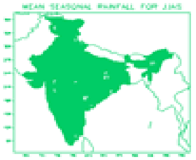
Present Seasonal Forecasting System for the Southwest Monsoon Rainfall Based on MME Approach: 2021

New Strategy for Long Range Forecast

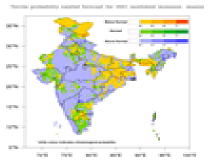
1st Stage Forecast

April

All India averaged Season (June – September) Rainfall



Spatial pattern of probability forecast for the Season Rainfall over the country

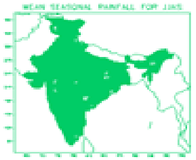


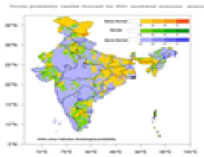
Based on Statistical and MME

2nd Stage Forecast

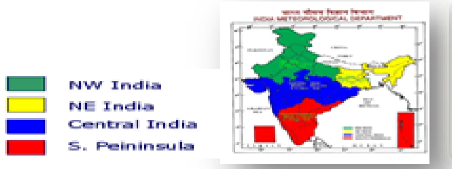
May

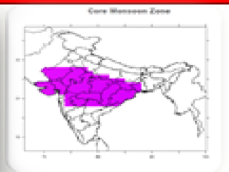
Update for the April forecast for the All India averaged Season Rainfall and spatial pattern of probabilistic forecast over the country





Forecast for Season Rainfall: for the Four Homogeneous Regions & Monsoon Convergence Zone (MCZ)





Based on Statistical and MME

Monthly Forecast

End of May, June, July & August for subsequent one month

Probabilistic Forecast for Monthly rainfall

Based on MME of Dynamical models

In addition, Forecast for Date of Monsoon Onset over Kerala in May

New Forecasting Strategy Based on MME:

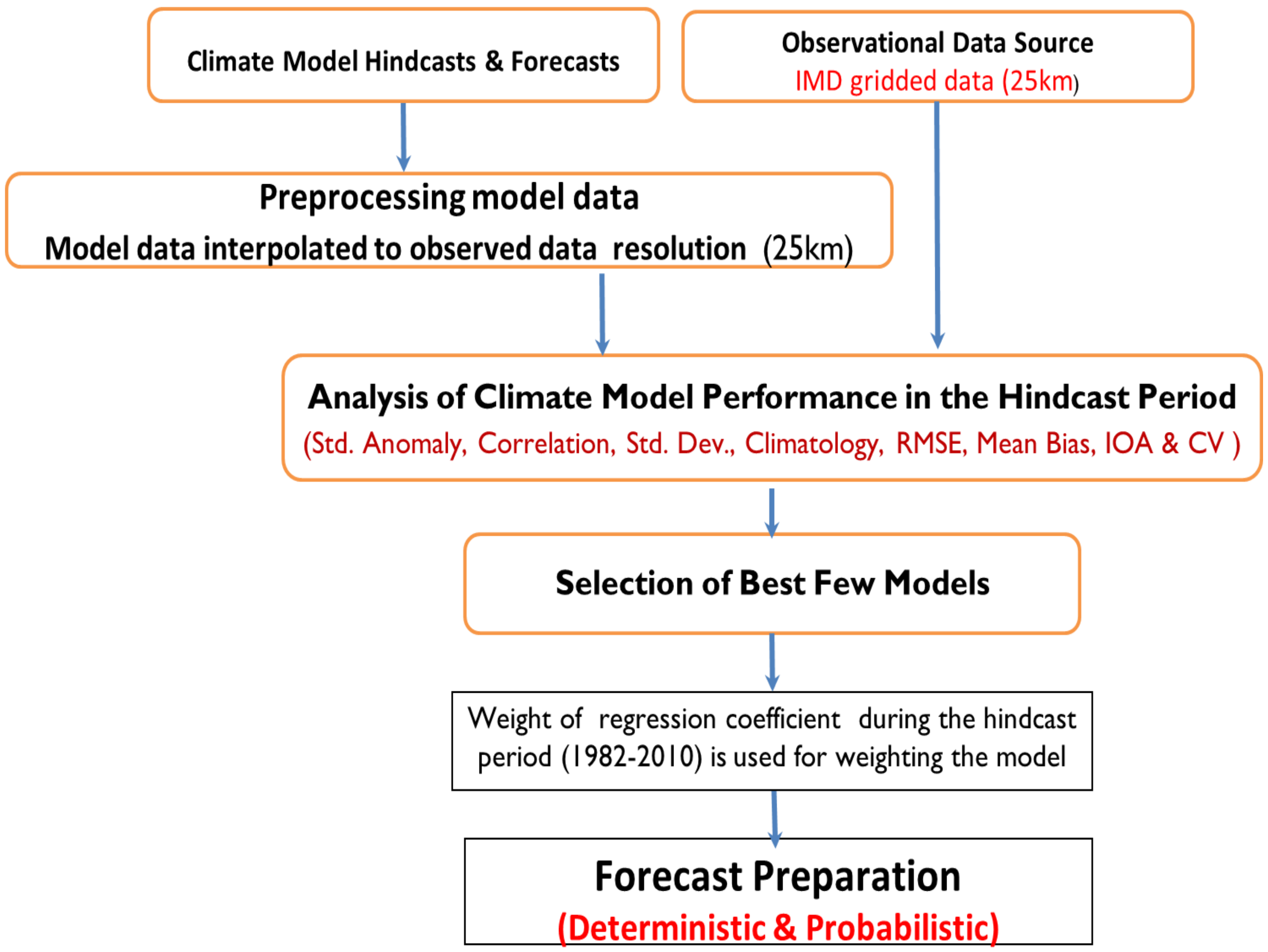
- Demands from different users and government authorities for forecasts of spatial distribution of seasonal rainfall along with the regionally averaged rainfall forecasts for better regional level planning of activities.

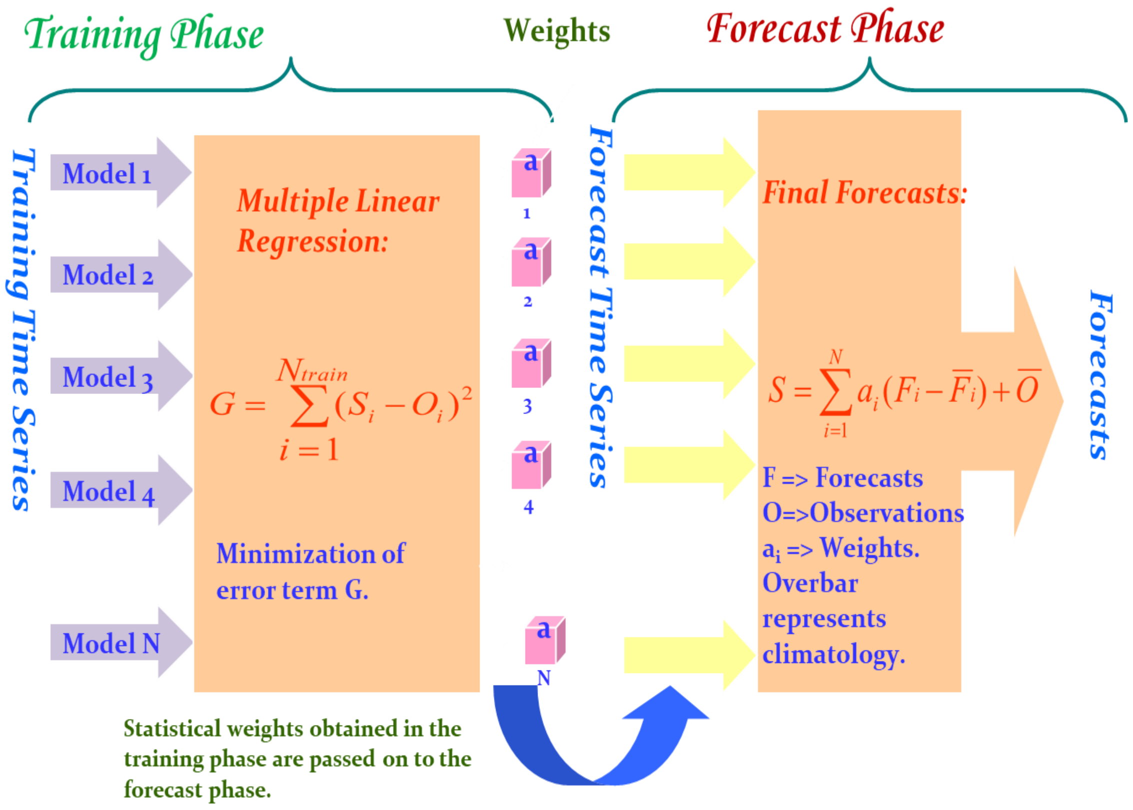
- For this, now a Multi-Model Ensemble (MME) forecasting system based on coupled global climate models (CGCMs) from different global climate prediction and research centers including the MMCFS

- MME is a universally accepted technique used to improve skill of forecasts and reduce forecast errors when compared to a single model-based approach. The performance improvements are completely attributed to the collective information of all models used in the MME forecasting system.

- CGCMs with the highest forecast skills over the Indian monsoon region including MMCFS have been used to generate MME forecasts.

MME Method Explained





Coupled Models Used for Multi Model Ensemble forecast

S.No	System name	Centre / Country	Hindcast Period	Source
1	MMCFS	IMD/India	1982-2010	IMD
2	NCEP CFSv2	NOAA, USA	1982 - 2010	NCEP-NMME/IRI
3	GOES	NASA	1982 - 2010	NCEP-NMME/IRI
4	GEM-NEMO	Canada	1982 - 2010	NCEP-NMME/IRI
5	CanCM4i	Canadian Meteorological Center	1982 - 2010	NCEP-NMME/IRI
6	COLA-CCSM4	NCAR/USA	1982 - 2010	NCEP-NMME/IRI
7	SEAS-5	ECMWF	1982 - 2010	Copernicus/IRI
8	JMA/MRI	JMA/Japan	1982-2010	JMA/Copernicus

Data from the above 8 climate models (CGCMs) are available real-time for preparation of Multi Model Ensemble forecast generation.

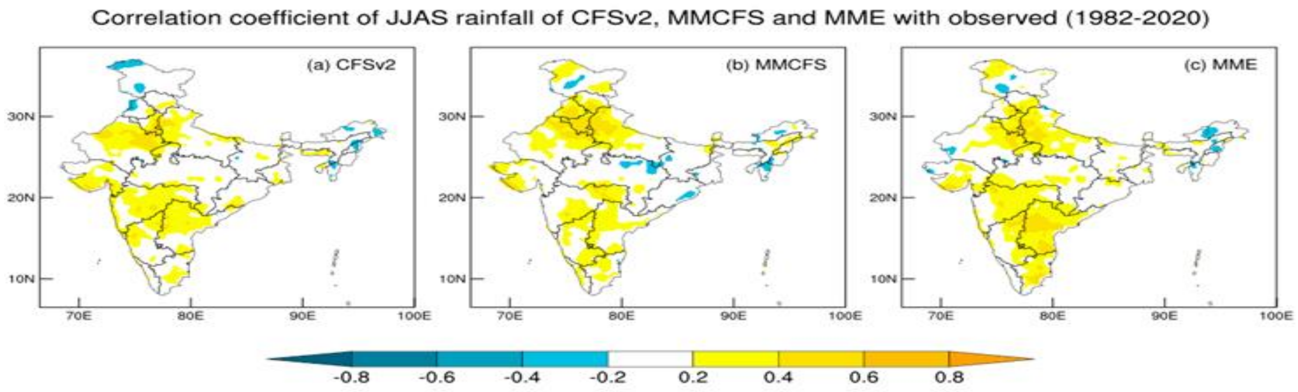
Hindcast Skill of Selected Climate Models:
JJAS Rainfall (All India) :1982-2010: March IC

S.No	Model	CC	IOA	MEAN (mm)	SD (mm)	CV	Bias (mm)	RMSE (mm)
OBS (ISMR)				872	82	9		
1	NCEP-CFSv2	0.58	0.28	515	46	8.93	-359	364.85
2	NASA-GOES	0.54	0.24	449	85	18.93	-424	431.75
3	GEM-NEMO	0.39	0.31	570	43	7.54	-303	312.78
4	MMCFS	0.34	0.3	552	84	15.22	-321	334.96
	MME	**0.67**	**0.59**	**765**	**52**	**6.8**	**-108**	**124.18**

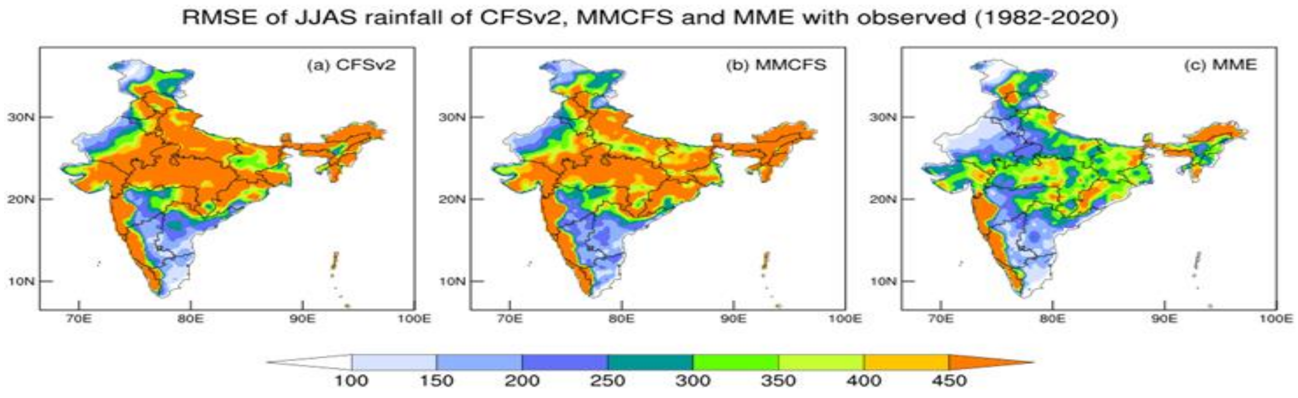
The skill (C.C, RMSE, IOA, RMSE, Bias etc) of Rainfall forecast for All India of 4 selected models shows that climate models has moderate skill for predicting All India Summer monsoon rainfall.

Index of agreement (IOA) as a standardized measure of the degree of model prediction error which varies between 0 and 1 proposed by Willmott (1981). The index of agreement represents the ratio of the mean square error and the potential error. The agreement value of 1 indicates a perfect match, and 0 indicates no agreement at all.

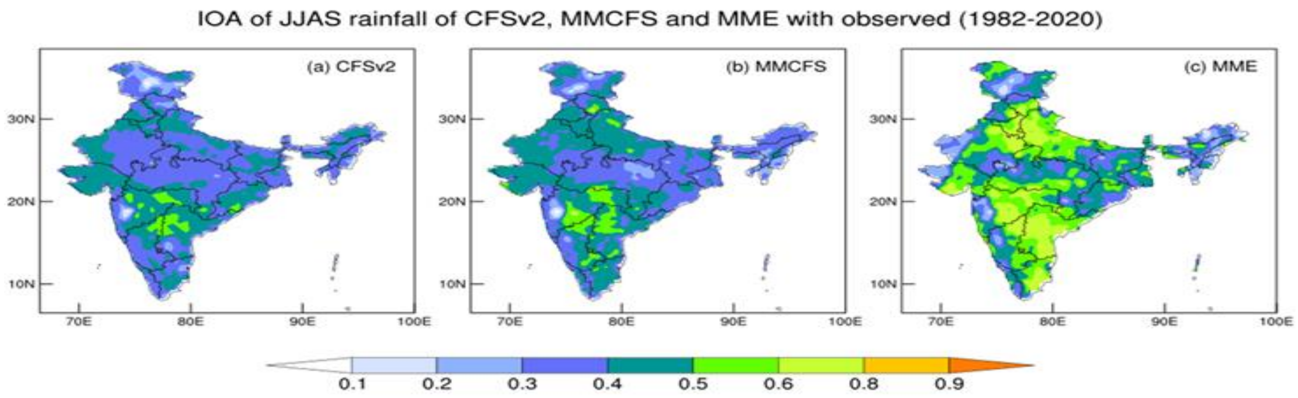
Spatial Hindcast skill (CC, RMSE & IOA): JJAS: 1982-2010: March IC MME, MMCFS and NCEP CFSv2



The Rainfall anomaly Correlation **(C.C)** is better than MMCFS and NCEP CFSv2. However monsoon trough region the skill is very poor.

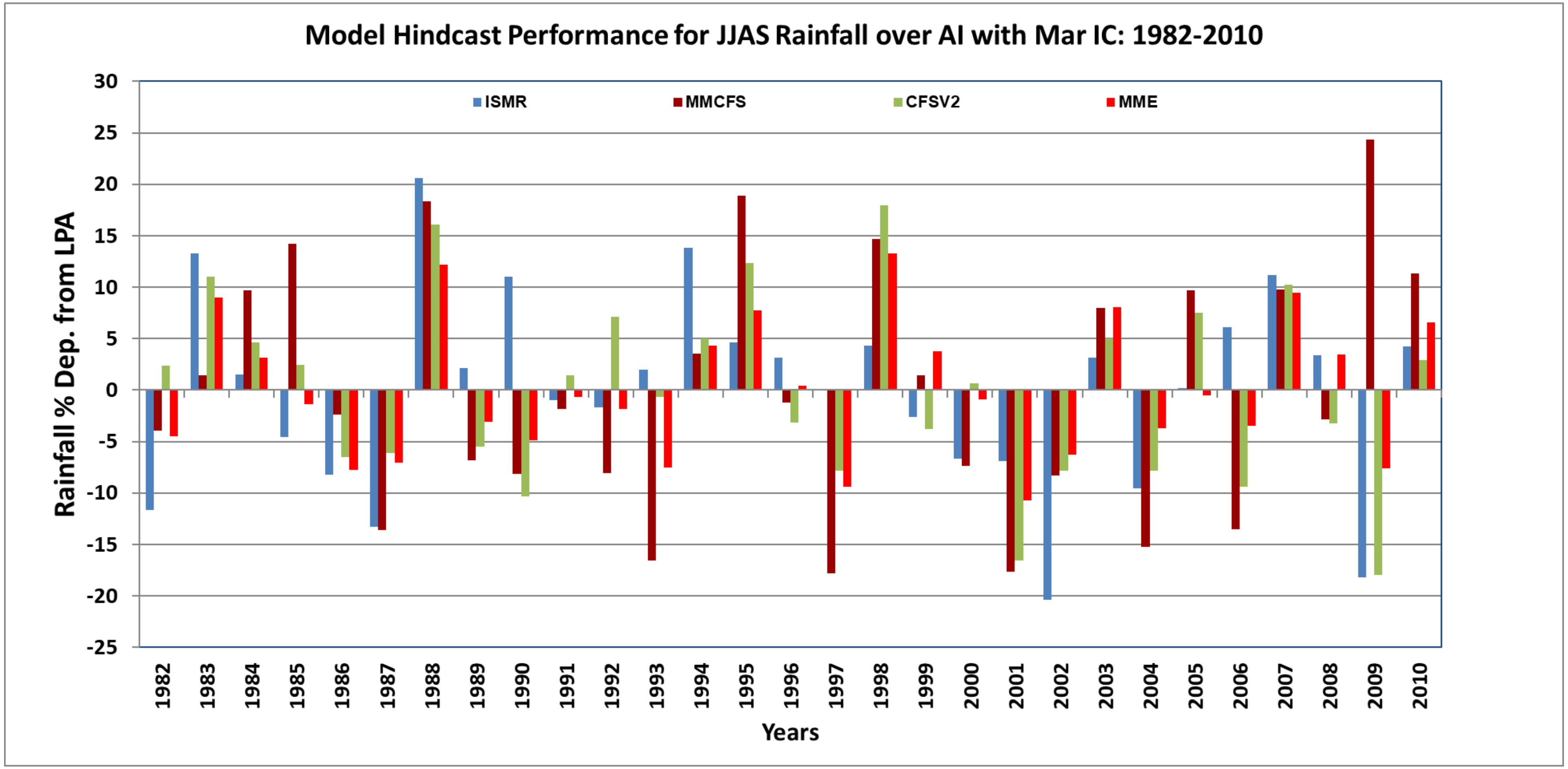


The **RMSE** of MME is better than MMCFS and NCEP CFSv2. However RMSE is more over Western Ghats and North Eastern region and monsoon trough region.



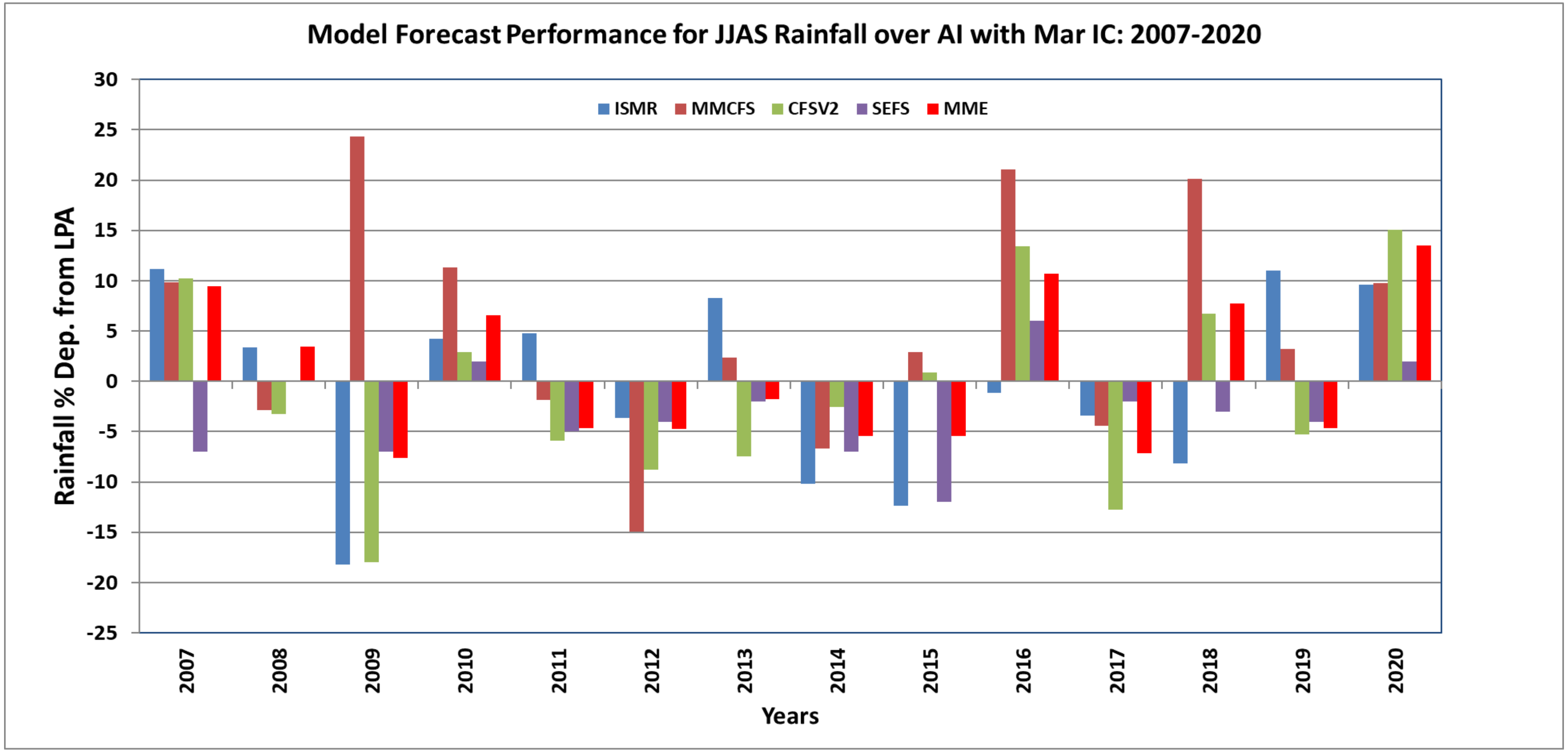
IOA: MME performs better over most regions compared to CFSv2 and MMCFS

Performance of MME, MMCFS and NCEP CFSv2 (March IC) Hindcast Period: 1982-2010 (All India)



The MME perform better than the MMCFS and CFSv2. In the year 2009 MMCFS could not indicate the rainfall deficiency.

Comparison of Forecasts SEFS (April) , MMCFS, CFSv2 and MME (Mar IC) from Various Models for All India: 2007-2020



Average Absolute Error			
MMCFS	CFSV2	SEFS	MME
11.37	8.73	7.71	6.99

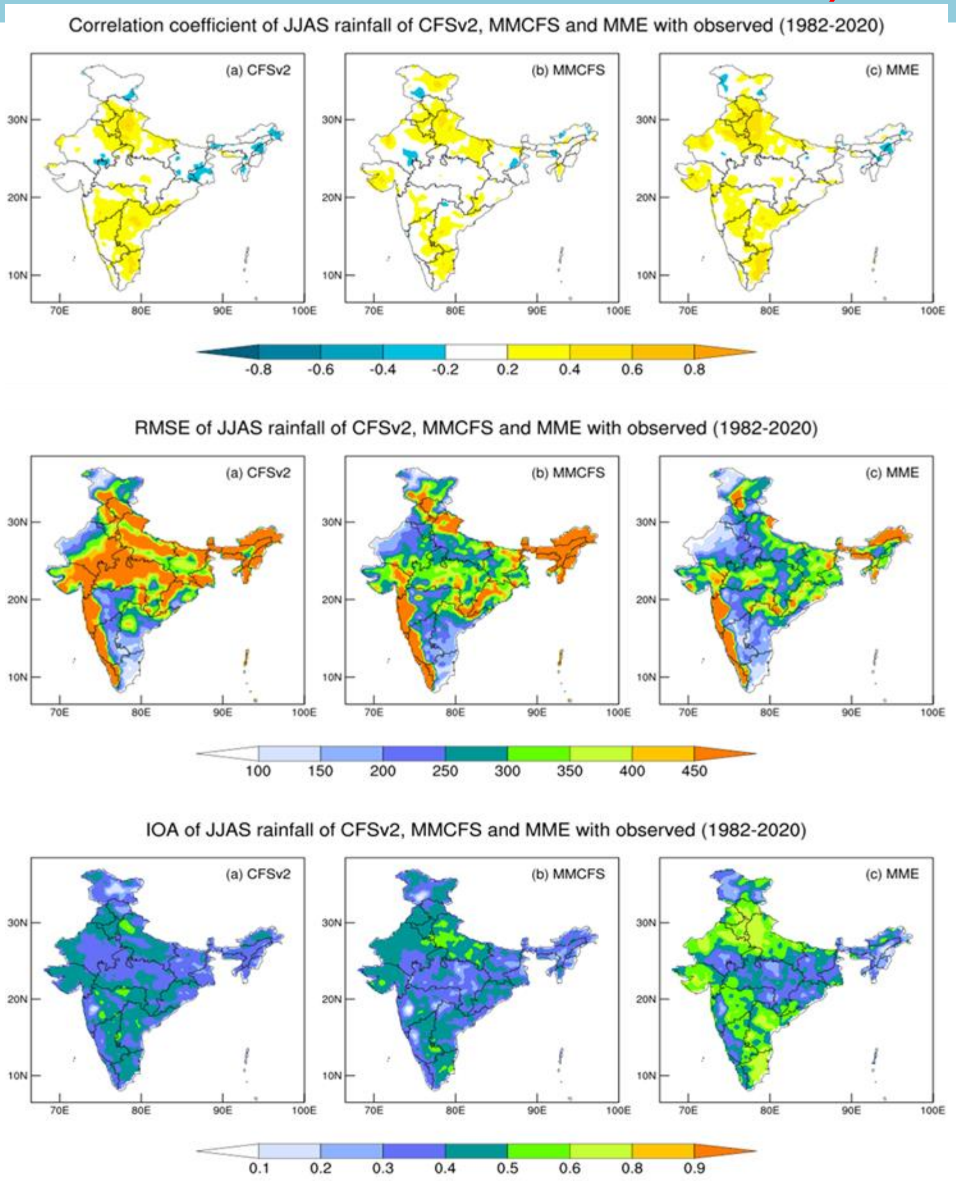
Absolute Error is lowest in MME

Skill of Climate Models (May IC)

Model	CC	IOA	MEAN (mm)	SD (mm)	CV	Bias (MM)	RMSE
Rainfall (ISMR)			872	82	9		
NCEP-CFSv2	0.54	0.4	658	47	7.14	-215	226
GEM-NEMO	0.48	0.33	587	53	9.03	-287	296
MMCFS	0.25	0.61	794	56	7.05	-80	117
JMA	0.15	0.41	666	85	12.76	-208	224
MME	0.43	0.73	845	88	10.41	-28.8	94.1

The Index of Agreement of the MME is highest than individual model and RMSE is lowest as compared to individual model. However, correction Coefficient (CC) of MME is less than CFSv2 and GEM-NEMO.

Spatial Hindcast skill (CC, RMSE & IOA): JJAS: 1982-2010: May IC MME, MMCFS and NCEP CFSv2

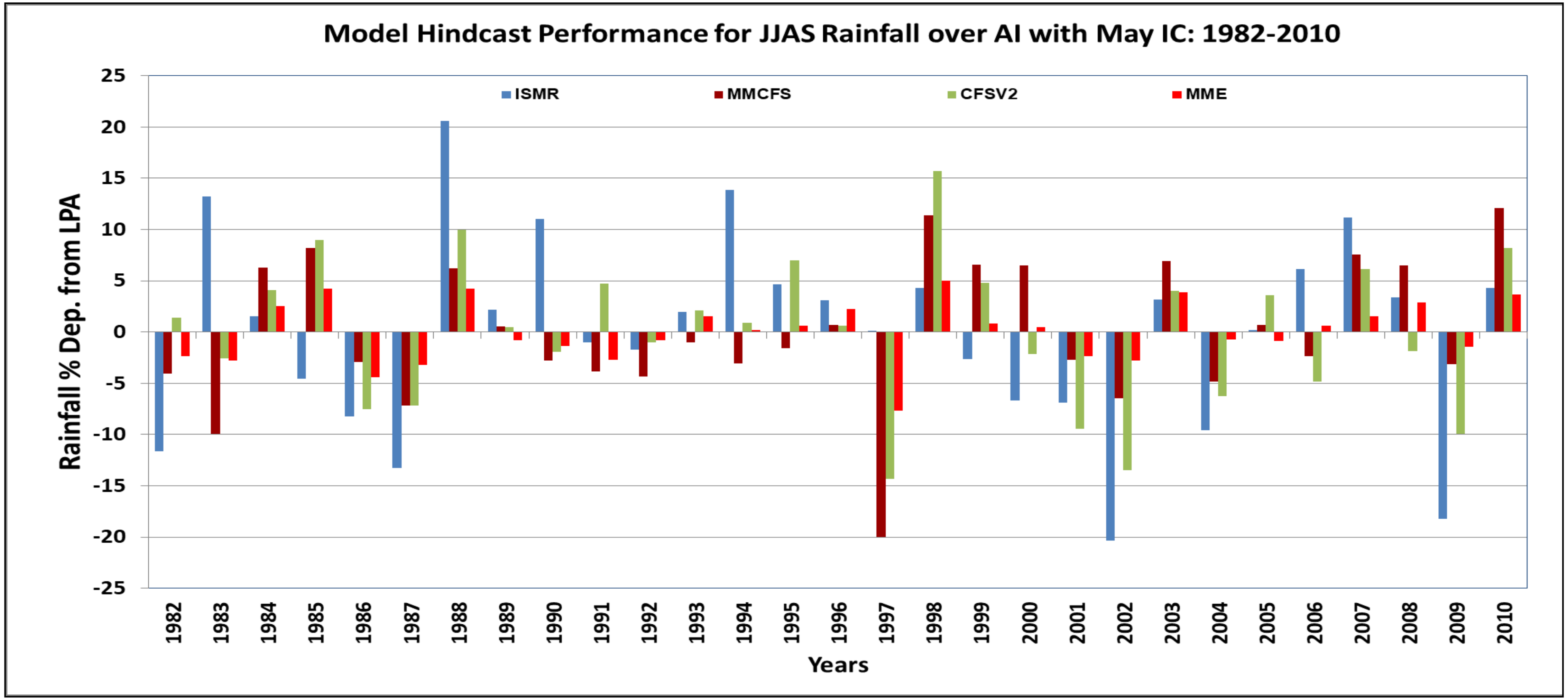


The Rainfall anomaly Correlation (C.C) is better than MMCFS and NCEP CFSv2 in most areas.

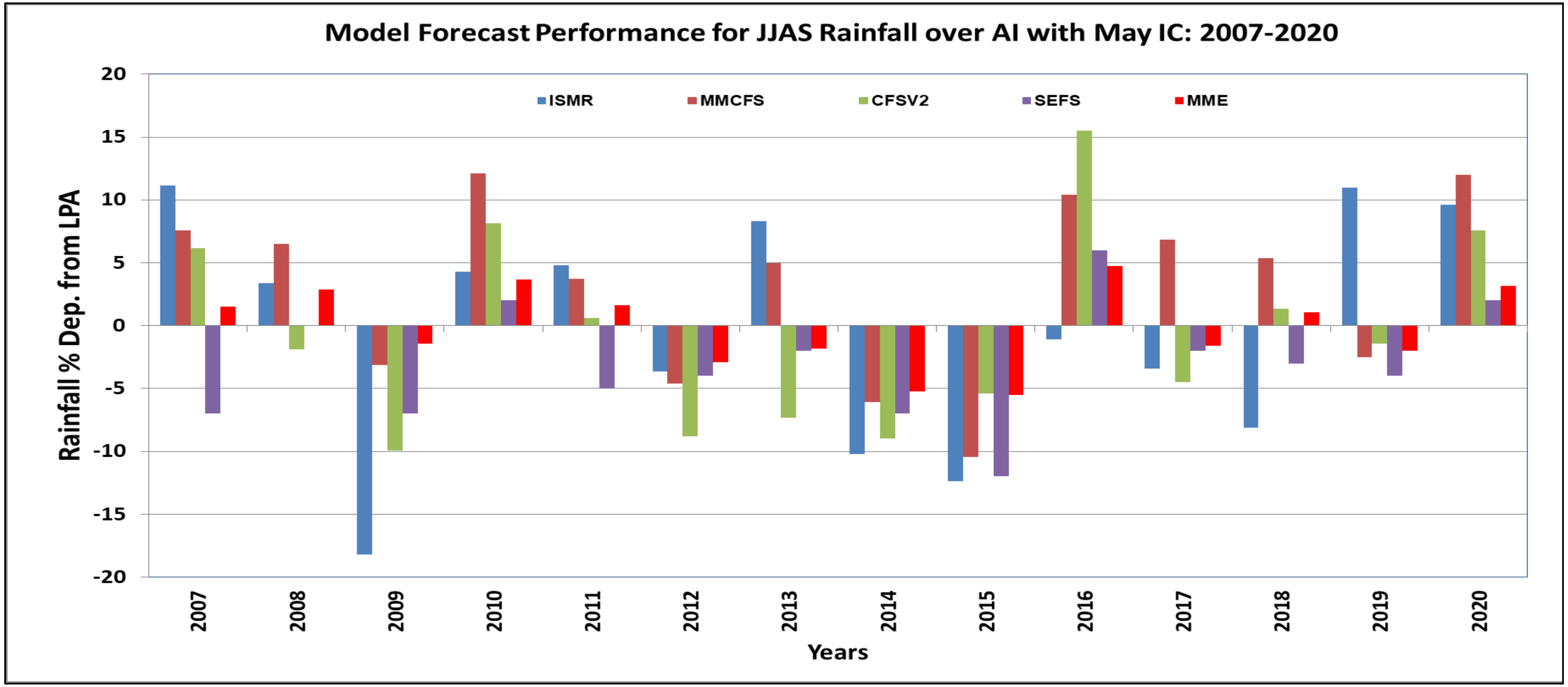
The RMSE of MME is better than MMCFS and NCEP CFSv2. However RMSE is more over Western Ghats and North Eastern region and monsoon trough region.

MME performs better over most regions compared to CFSv2 and MMCFS

Performance of MME, MMCFS and NCEP CFSv2 (May IC)
Hindcast Period: 1982-2010 (All India)



Comparison of Forecasts SEFS (April) , MMCFS, CFSv2 and MME (May IC) from Various Models for All India: 2007-2020



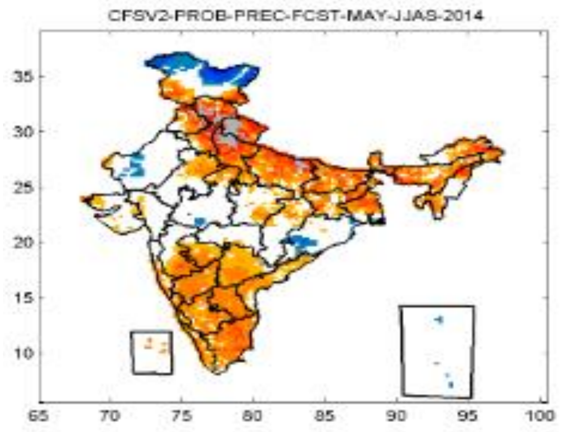
Absolute Error is lowest in MME

Average Absolute Error			
MMCFS	CFSV2	SEFS	MME
6.59	6.95	6.6	6.41

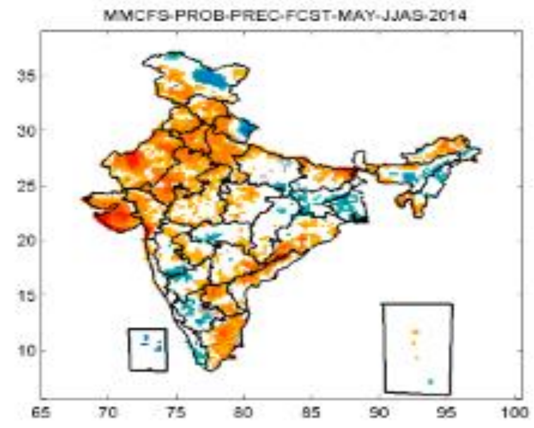
Rainfall Probability Forecast Verification for Deficient Rainfall Years (2014 & 2015) : May IC

2014

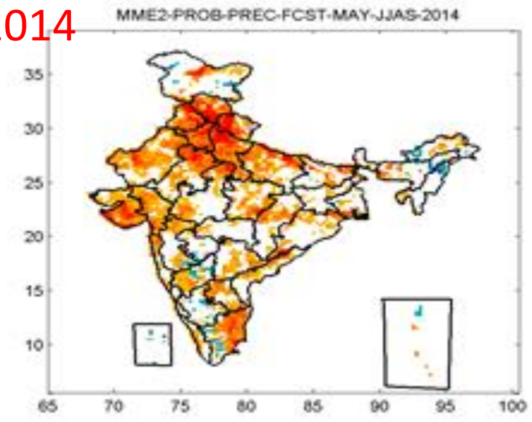
NCEP CFS2



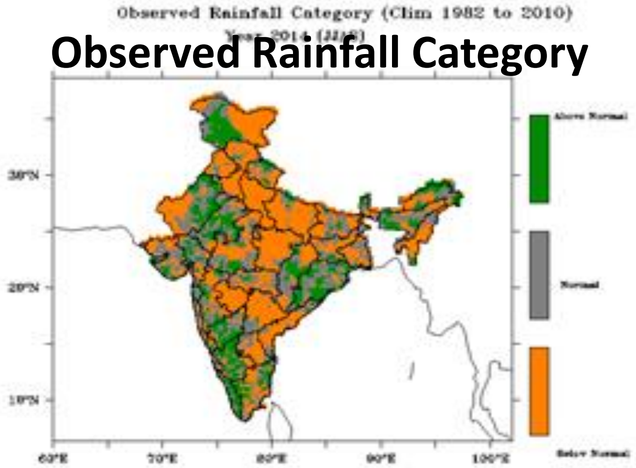
MMCFS

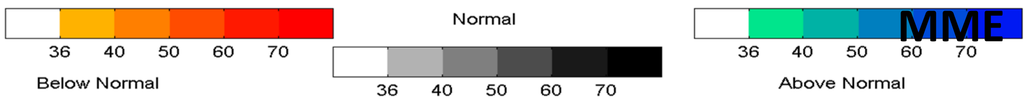


MME



Observed Rainfall Category

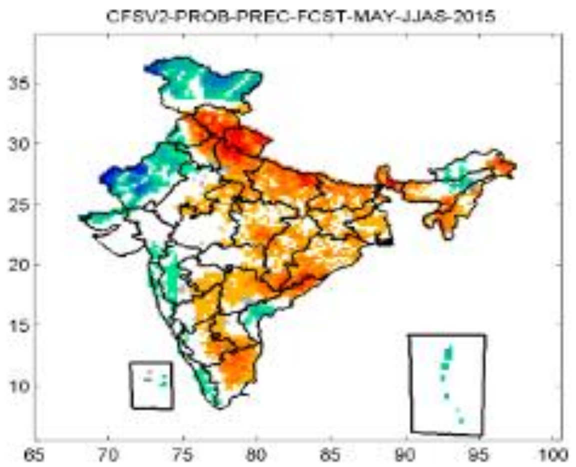




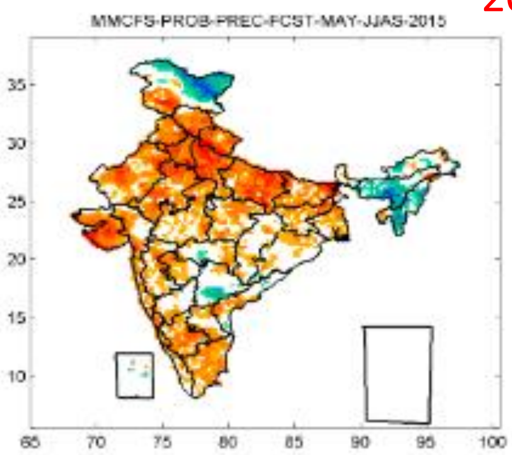
MME

2015

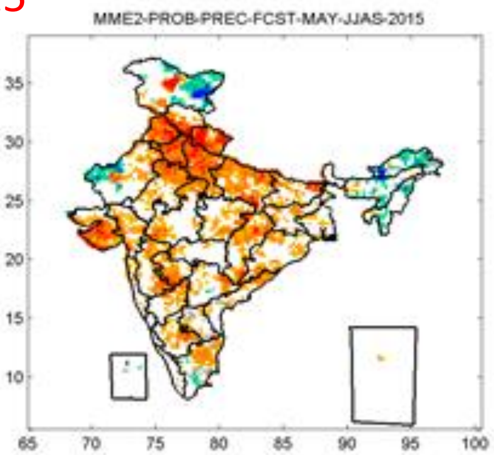
NCEP CFS2



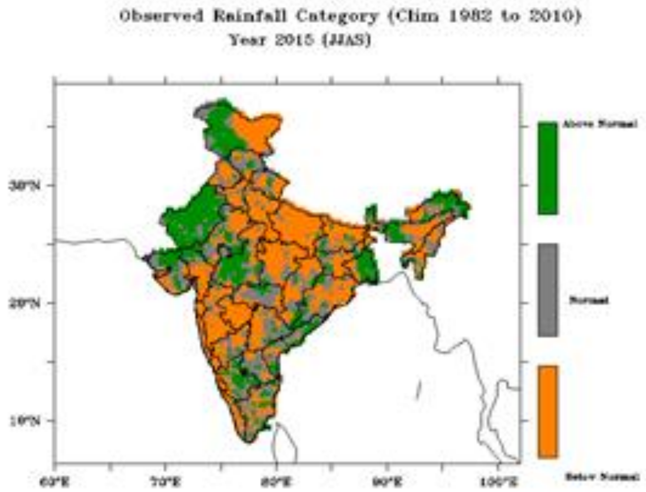
MMCFS



MME



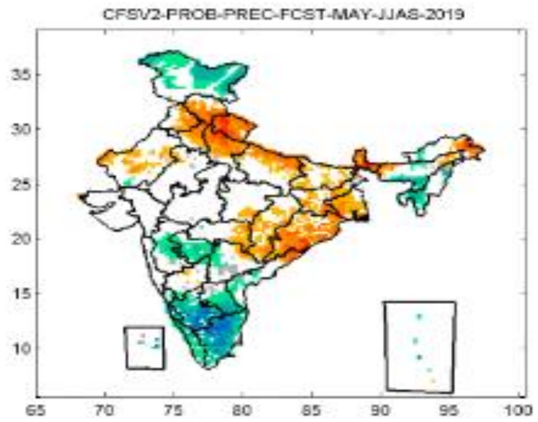
Observed Rainfall Category



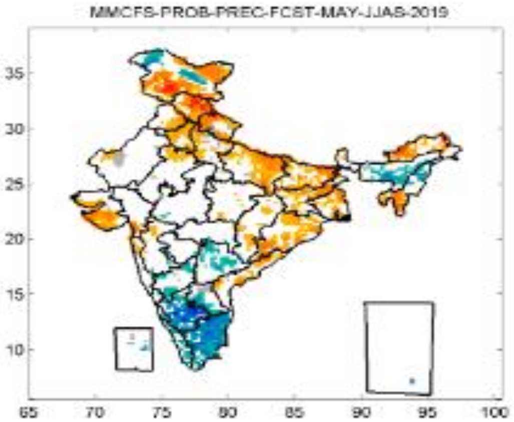
Spatial Rainfall probability forecast verification for Excess Rainfall Years (2019 & 2020) (May IC)

2019

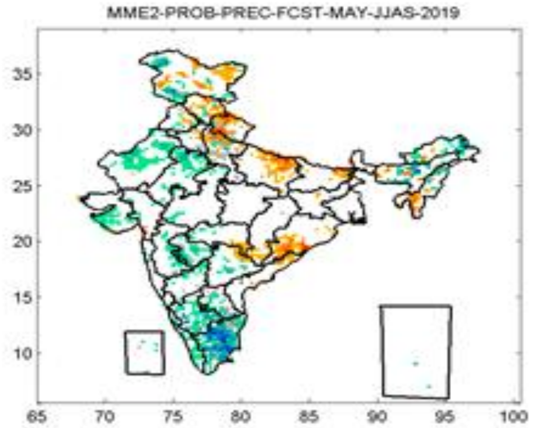
NCEP CFS2



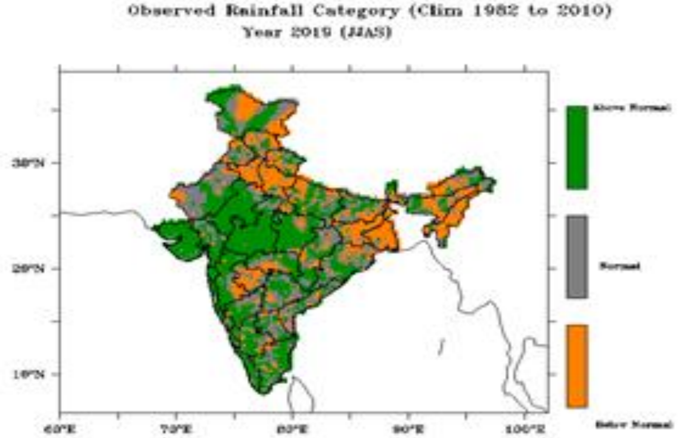
MMCFS

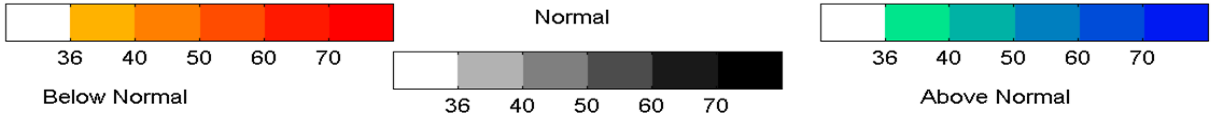


MME



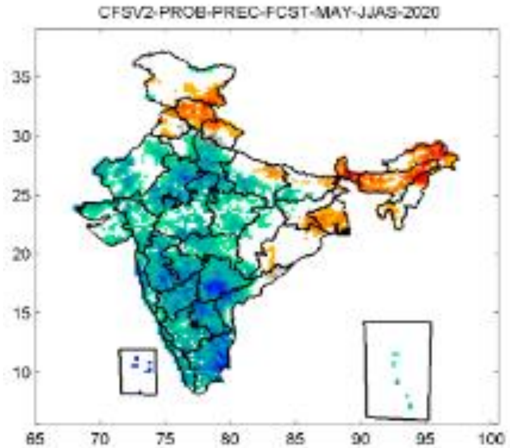
Observed Rainfall Category



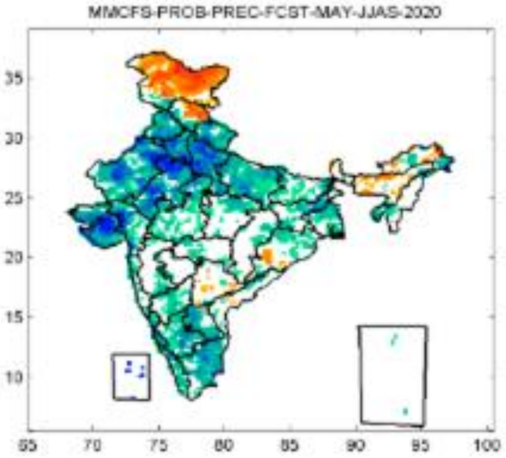


2020

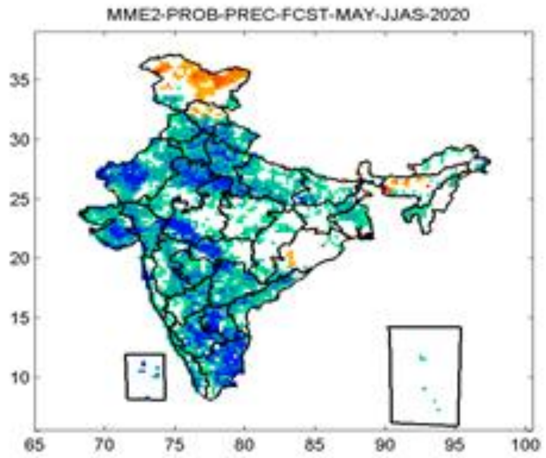
NCEP CFS2



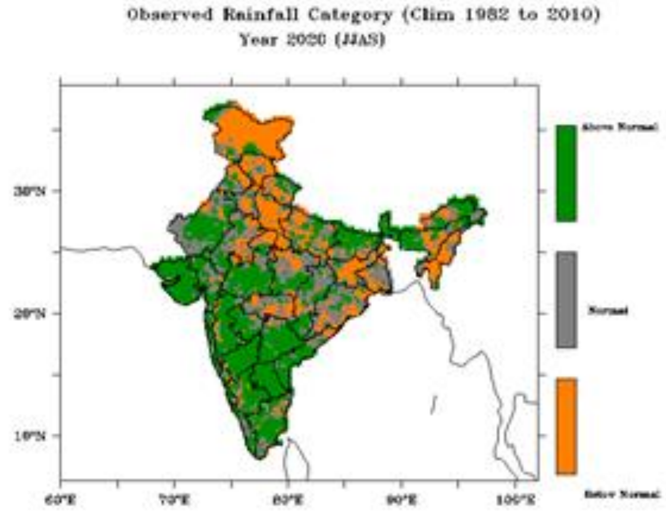
MMCFS



MME

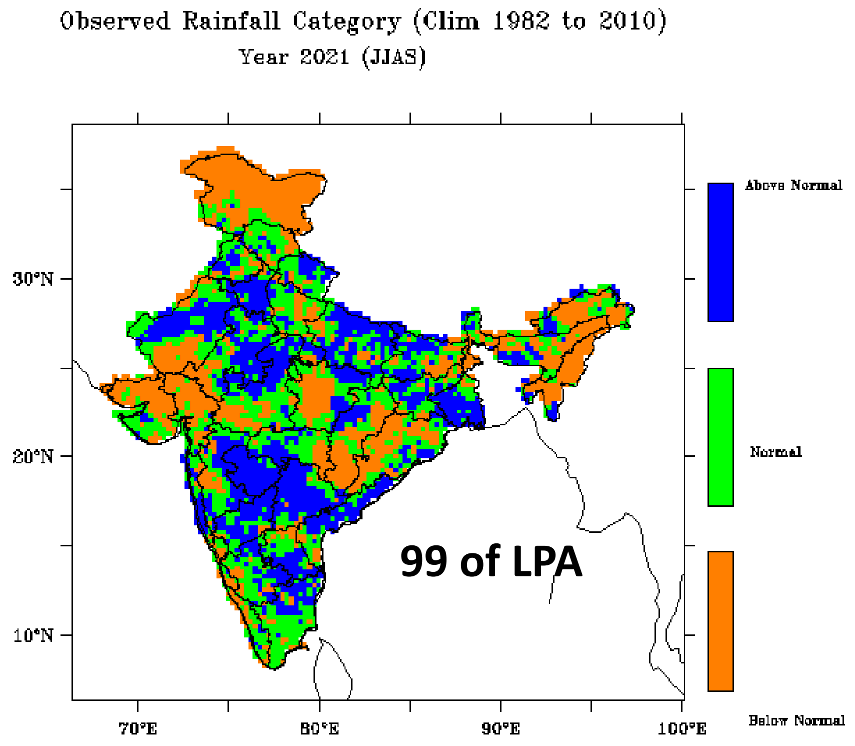


Observed Rainfall Category



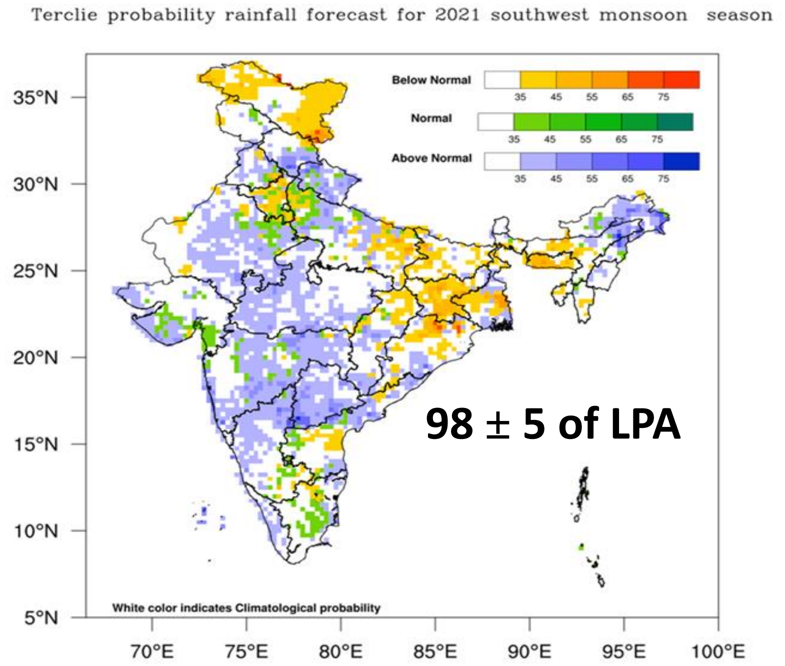
Verification of 2021 JJAS Seasonal rainfall forecast

Observed Rainfall Category (JJAS 2021)

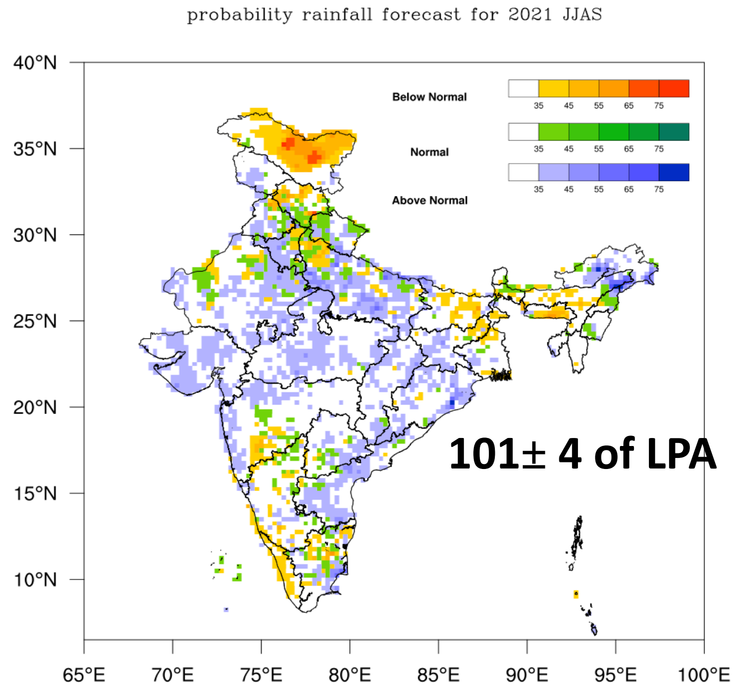


Rainfall Probability Forecast for JJAS Season

March IC



May IC



Above normal rainfall observed over many parts of North India, Central India and Eastern coastal India were very much matching with the forecast . Similarly, below normal rainfall observed over the extreme north India, some parts of North East India also as per the issued forecast. However, the observed below normal rainfall over some parts of north-west India and central and adjoining east India could not be predicted.

Conclusions

- Since first operational forecast in 1886, IMD has used various approaches to generate operational forecast for Indian summer monsoon rainfall.
- Traditionally, IMD has been using indigenously developed Statistical Models with regular updates and improvements.
- The statistical ensemble forecasting (SEFS) showed improved skill in the operational forecasting of ISMR compared to previous Statistical Models.
- However, the statistical model approach has limited skills for predicting rainfall averaged over smaller regions and in predicting spatial distribution of rainfall as required by the users.
- The seasonal forecasting system developed under Monsoon Mission (MMCFS) has skill for forecasting ISMR comparable to that of SEFS. But needs to be further improved to make skilful prediction for the monsoon prediction over smaller regions.
- The newly implemented multimodal approach has better skill in the prediction of monsoon rainfall over India compared to individual dynamical models used to built the MME as well as compared to SEFS.
- There is further scope for the improvement of skill of the seasonal forecasting over smaller regions.

Thanks