Modelling the Monsoon

Monsoon Mission

- ✓ Short Range
- ✓ Extended Range
- ✓ Long Range
- ✓ Model developments

The IITM Earth System Model

Ravi S. Nanjundiah

4th December 2019

Monsoon Mission Phase-II

Objectives

- To improve **operational forecast skill** over the country and develop relevant climate **applications for agriculture, hydrology and power sectors**.
- To develop and improve a **state-of-the-art dynamical modelling framework** for improving prediction skill of
  - Seasonal and Extended Range prediction
  - Short and Medium range (up to 2 weeks) predictions

Major Achievements

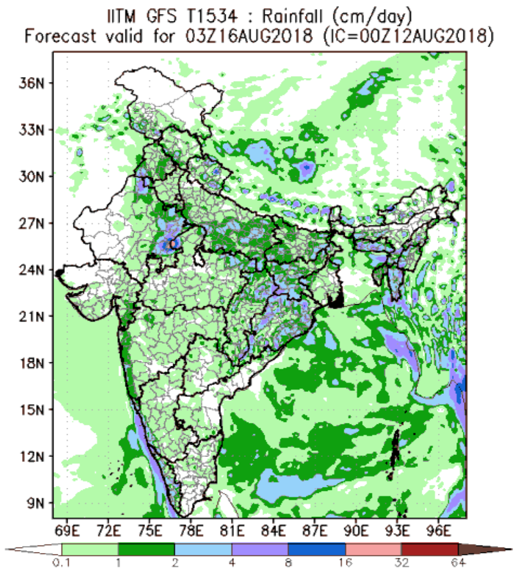
- **Highest resolution ensemble prediction system:** Has been setup and operationalized, can capture extremes with reasonable skill.
- **Extended range prediction system:** Setup using coupled grand ensemble prediction system. The MME skill is as good as ECMWF's ERP skill.
- **In-house developmental activities** (indigenous developmental activities): Considerable improvement in prediction skill of ISMR (Skill Improvement from 0.49 to 0.70 > 40% improvement; > 20% more than what was envisaged).
- **Implemented almost all developmental modifications** carried out by different scientists at IITM and PIs of sponsored research in MM-I
- **Spectral cubic Octahedral grid is implemented in GFS** model in collaboration with ECMWF and CCCR
- **Implemented weakly-coupled data assimilation (WCDA)** system and analysis is being created in collaboration with UoM
- **Developed downscaling and bias correction techniques** for extended range prediction.
- **Developed signal amplification techniques** for ERP.
- **Coupled hydrology model to CFS** to estimate river-runoffs to Ocean Model: improved air-sea interactions.
- **Agriculture and Hydrology applications** are initiated.

New Development in GFS

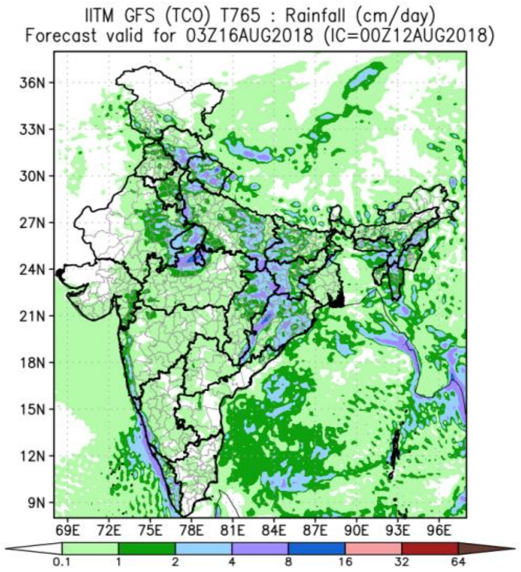
- New LULC (Land use Land Cover data from ISRO)
- New Scale Aware Convection (CS) in GFS
- New Microphysics (WSM6) modified with CAIPEEX data (Collaboration with Ziad Haddad and Maithili Saran) in GFS
- New Dynamic Core T → Tc → Tco (In collaboration with ECMWF) tested in GFSTco765

Near future implementation

- Stochastic Multiscale multicloud Parameterization in GFSSPPT in GFS (similar to ECMWF)



GFS T1534



GFS TCO 765

Tco765=T1534

Major Update in Dynamic Core

Spectral Cubic Octahedral grid

Conventional Spectral grid:

- **Not scalable**
- **I/O**
- **Artificial diffusion damping**
- **Negative tracer**

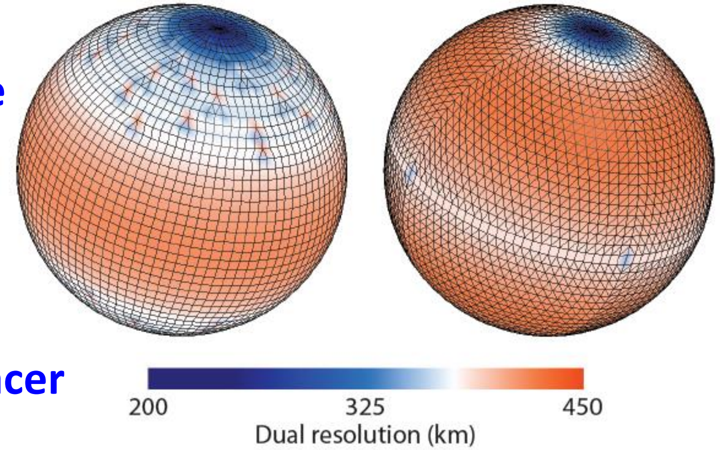
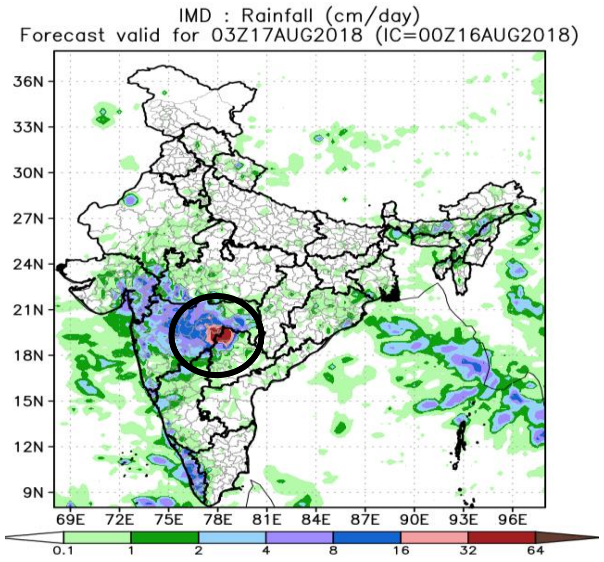
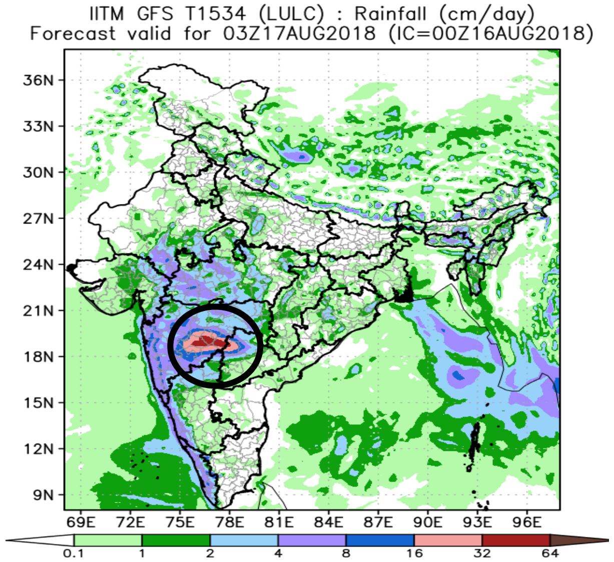


Figure (adopted from ECMWF News Letter 146) demonstrates that the octahedral mesh (right) has a locally more uniform dual-mesh resolution than the mesh (left).

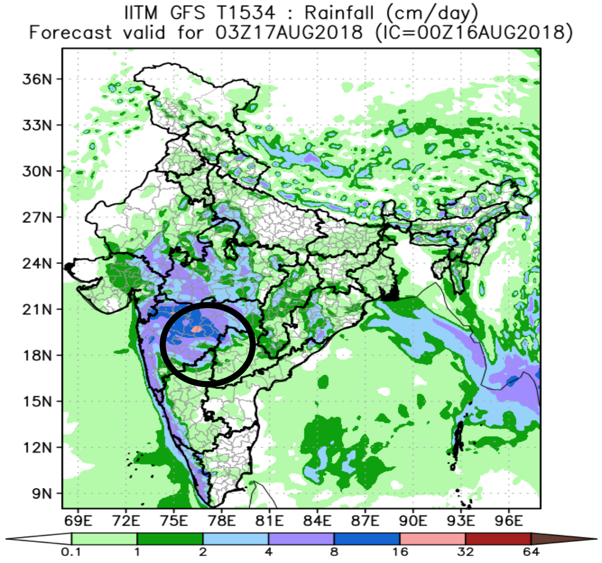
Rainfall (mm/day) time series over Kerala during 06-19Aug, 2018



IMD OBS



GFS with Modified LULC

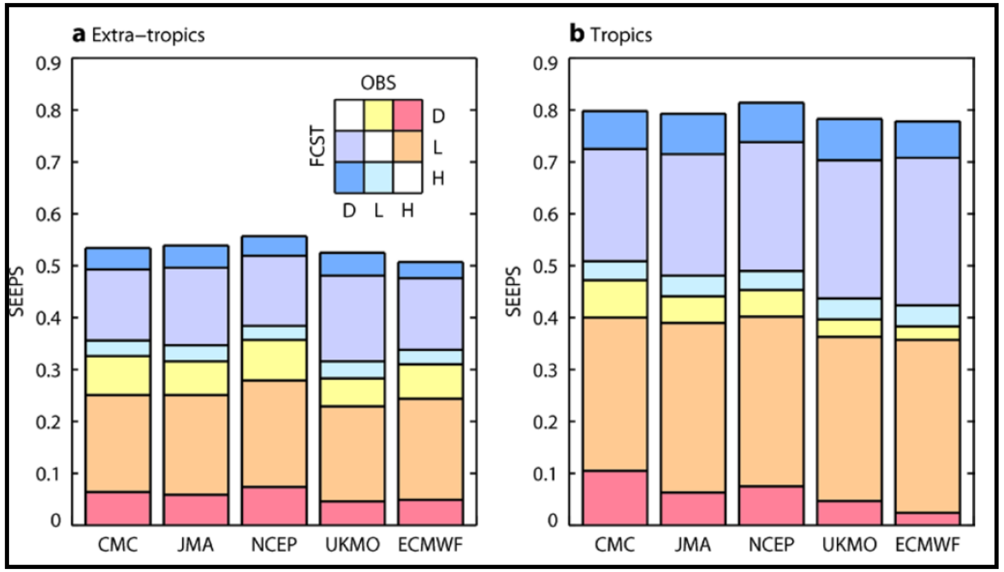


GFS with default LULC

- ✓ At 24hr lead, Chikira and Sugiyama (CS) convection scheme works better.
- ✓ With improved LULC, there is an improvement of heavy rainfall forecast

Comparison Precipitation forecast skill global model 2010/2011

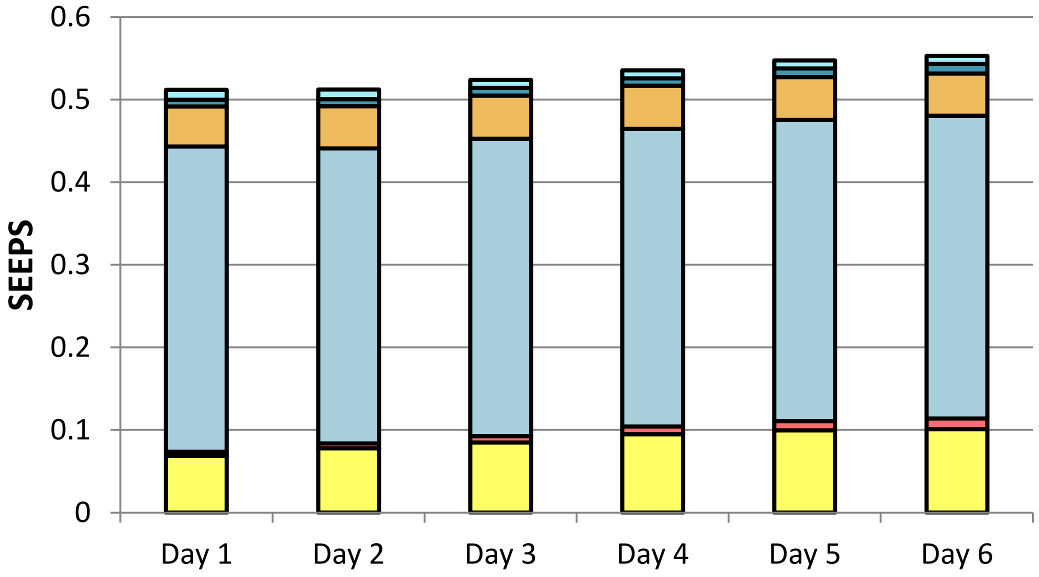
(Stable Equitable Error in Probability Space)
Global Models for Extra-tropics and Tropics

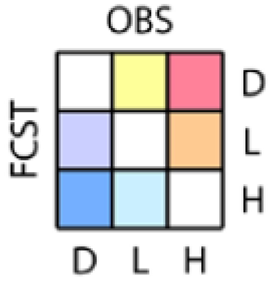


SEEPS is based on a 3×3 contingency table and measures the ability of a forecast to discriminate between 'dry', 'light precipitation', and 'heavy precipitation'.

As per Haiden et al 2012, ECMWF, TM 665

(Stable Equitable Error in Probability Space)
SEEPS for GFS T1534 JJAS 2018 for Indian land points only

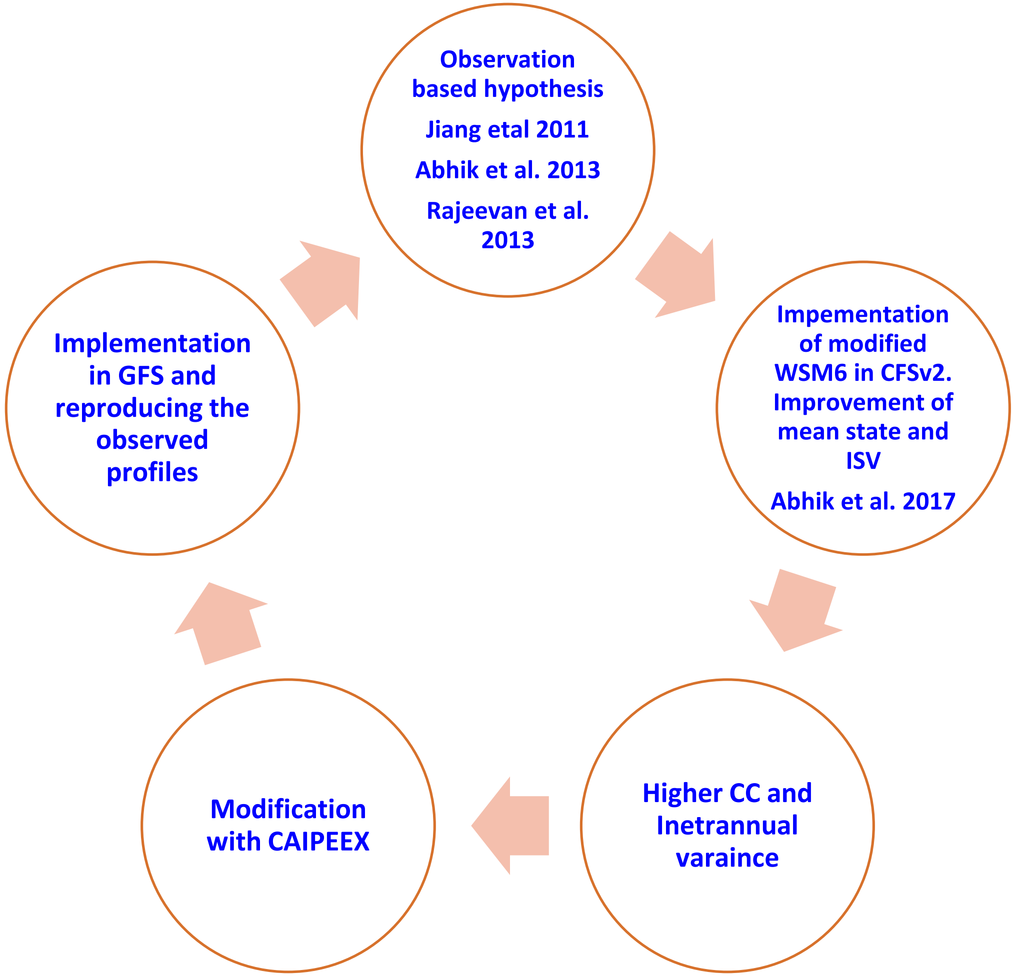


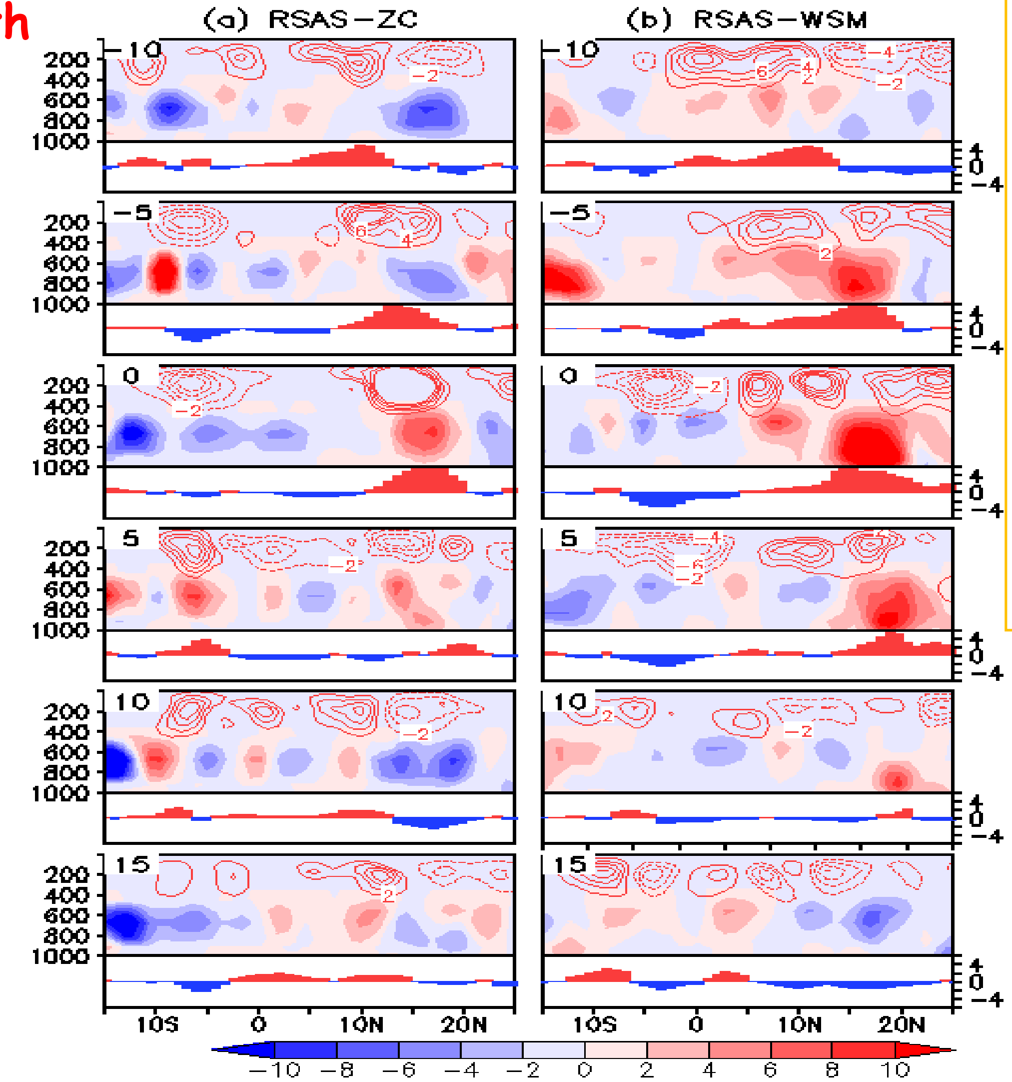


Lesser the value better the score.

Dry- 0-0.5 mm
Light- 0.5-50 mm
Heavy- >=50 mm

Improving Cloud Microphysics constrained with Indian data (RAC reco)





RSAS-ZC: Zhao and Carr (ZC) cloud microphysics scheme with simplified Arakawa-Schubert (RSAS) convection scheme.

RSAS-WSM: Six-class WRF single moment (WSM6) cloud micro-physics scheme with Revised SAS (RSAS) convection scheme.

Lag composite of CLW (shaded) and CLI (red contour, solid (+ve) and dashed (-ve)) during strong event averaged over 70E-90E, corresponding rainfall anomalies plotted in the bottom in each plot.

CFSv2 with RSAS-WSM is able to better simulate

- ✓ The large-scale organized northwest-southeast tilted structure of rain band
- ✓ Reasonable large-scale or stratiform rainfall associated with the northward propagating strong BSISO events
- ✓ The pressure-latitude profiles of cloud liquid water (CLW) and cloud ice (CLI) show more realistic steady northward propagation

Ganai et al. 2019, Clim. Dyn.

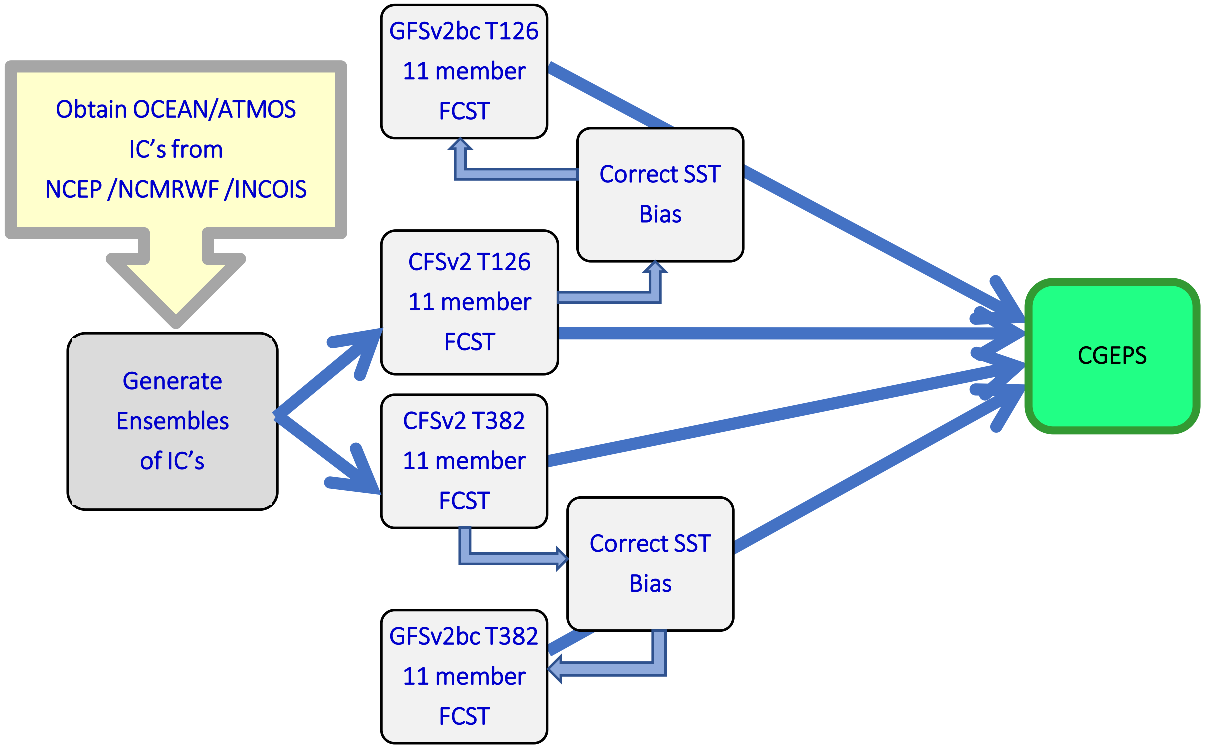
Development in ERPAS so far

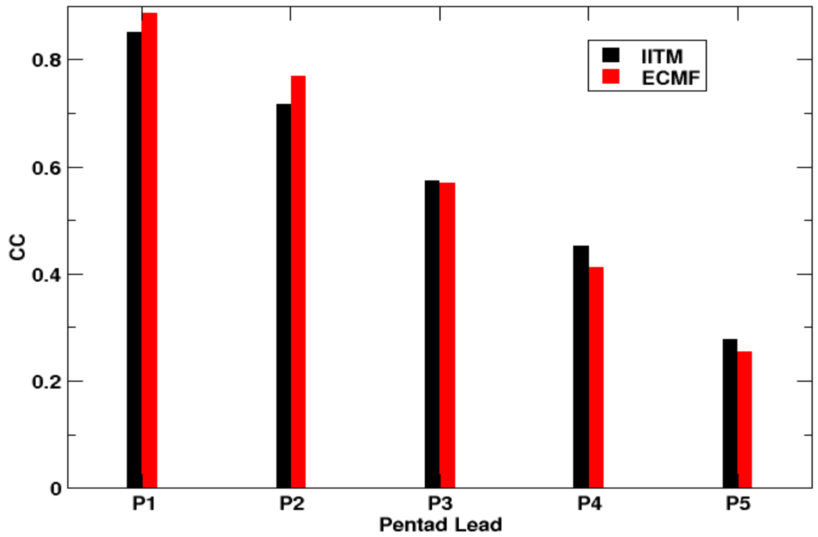
1. **Developed perturbation technique for Initial conditions**
2. **Developed technique for boundary condition (SST) bias correction**
3. **Developed CFS based MME**
4. **Develop better MISO and MJO monitoring techniques for operational predictions**
5. **Develop better technique for onset, withdrawal, heat wave forecast**
6. **Develop downscaling and bias correction techniques***
7. **Develop signal amplification techniques ***

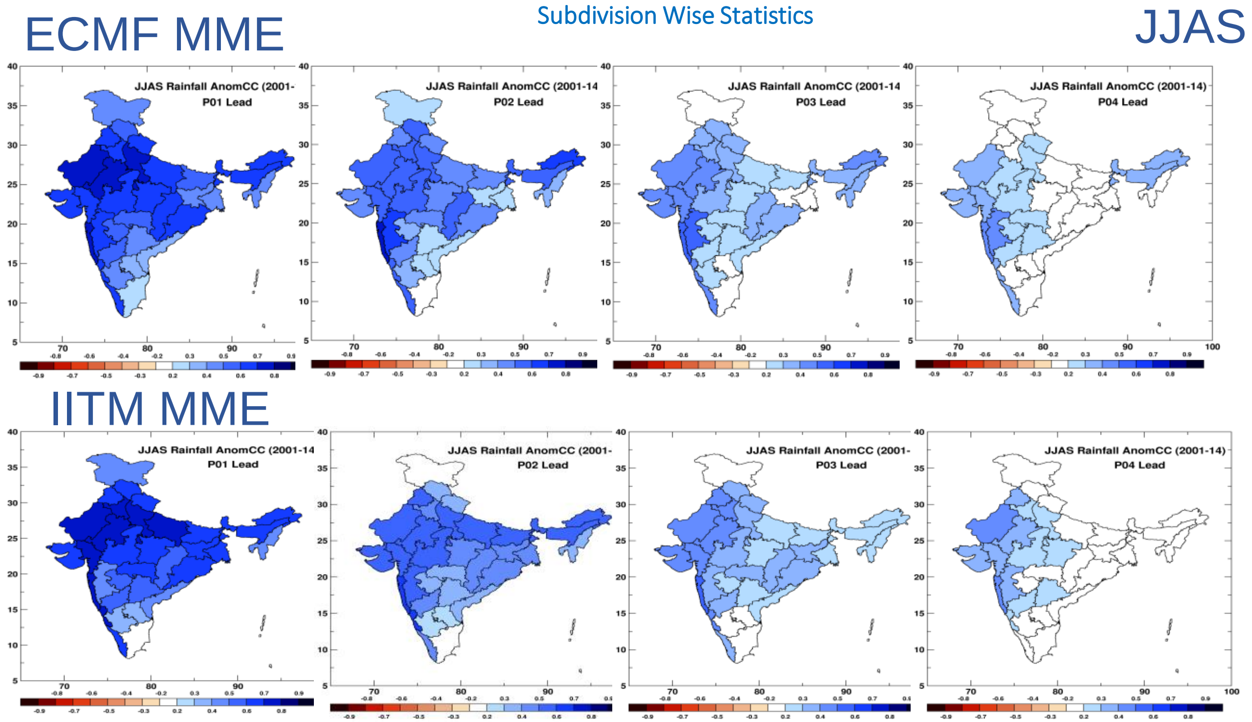
* Not implemented yet

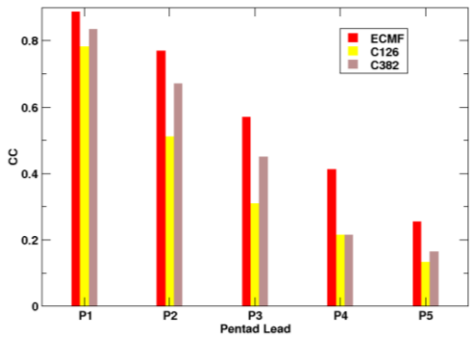
Task 3: Development of MME

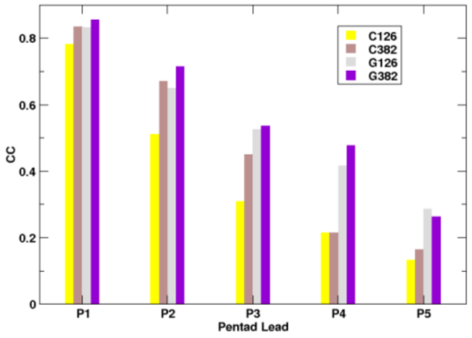
An Example of IITM Ensemble Prediction System









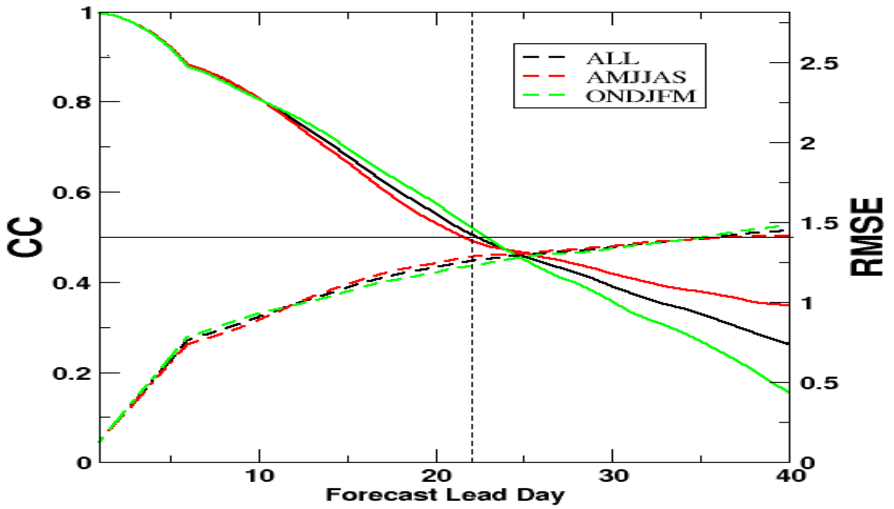


Skill of CFST126/T382 is much less than ECMWF in longer leads

Skill improved due to bias correction

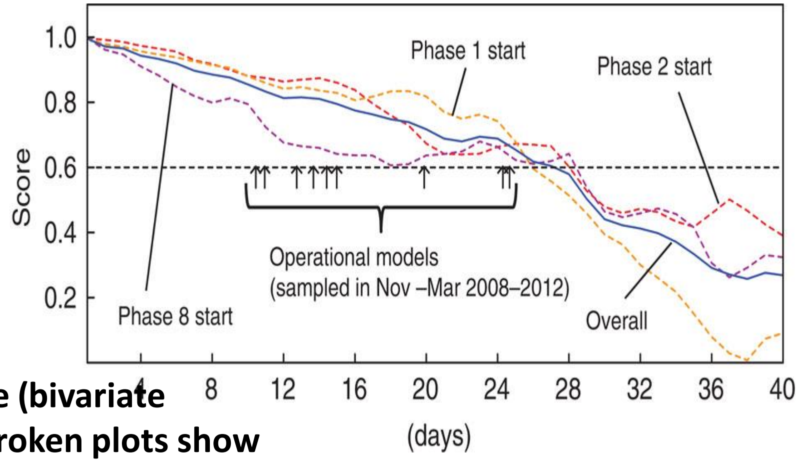
Task 4: MJO Monitoring and Forecast-IITM ERPAS

IITM ERP system



IITM ERP system has useful prediction skill (bivariate CC) up to around 22 days. Winter skill is slightly higher than the summer skill.

NICAM



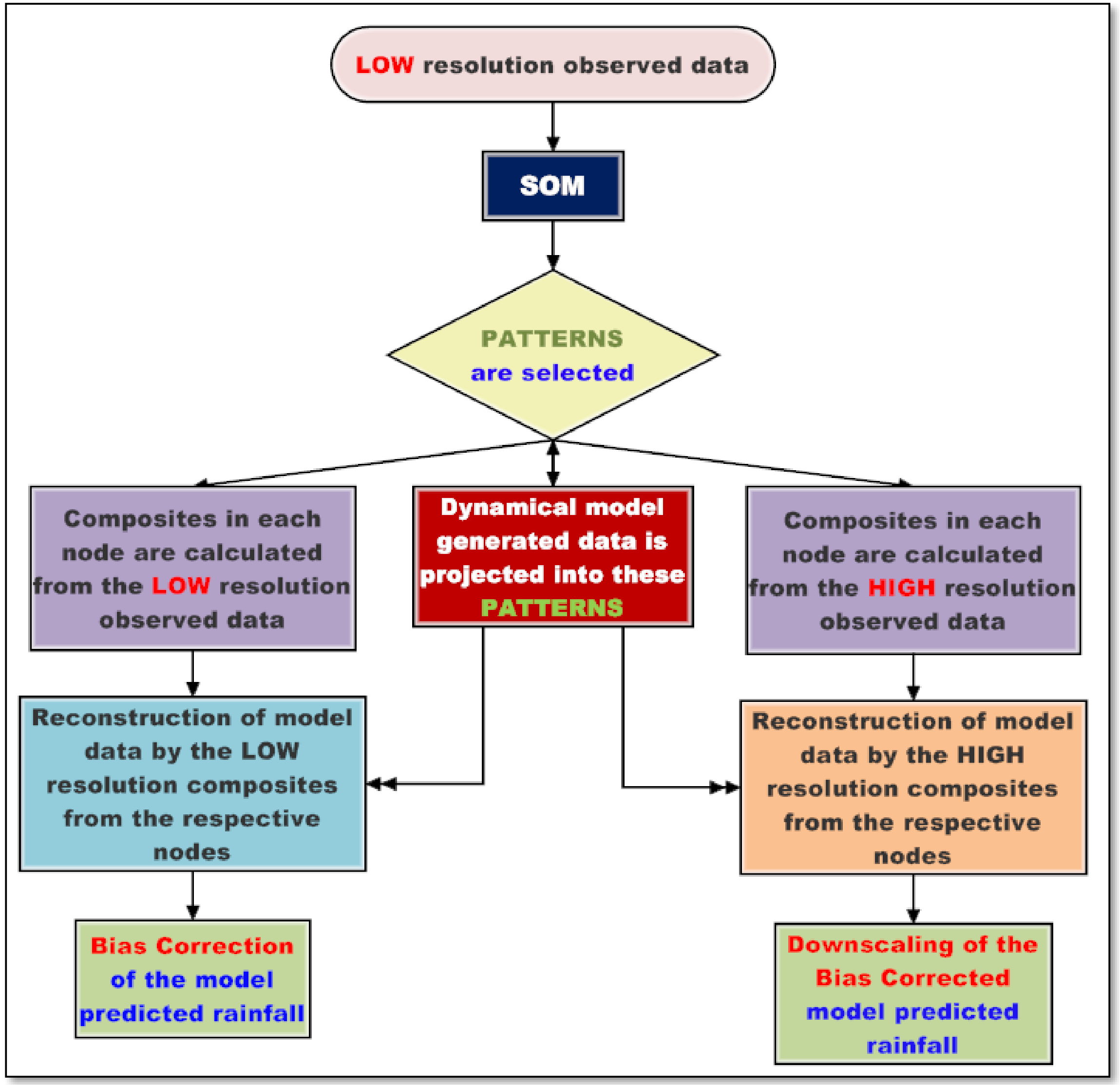
It is found that skill in predicting MJO by IITM model is at par with Very High resolution NICAM model.

Blue solid plot shows the overall skill score (bivariate correlation; COR) for all 54 simulations. Broken plots show COR for groups of simulations initialized at phase 8 (purple, 17 members), phase 1 (orange, 18 members) and phase 2 (red, 19 members).
Arrows indicate the durations COR>0.6 is maintained by recent operational models

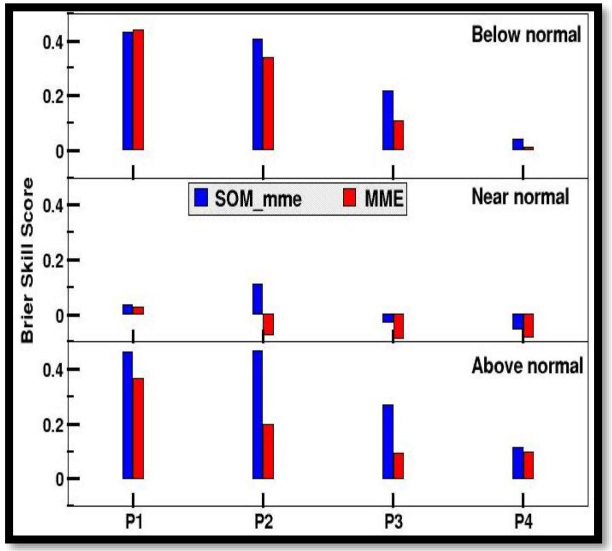
MJO forecast is based on 44 ensemble member. Taking 11 member each from CFS (T126 & T382) and bias corrected GFS (T126 & T382). Hindcast period 2001 -2016.

Miakawa et al., Nature Comm (2014).,5, doi:10.1038/ncomms4769

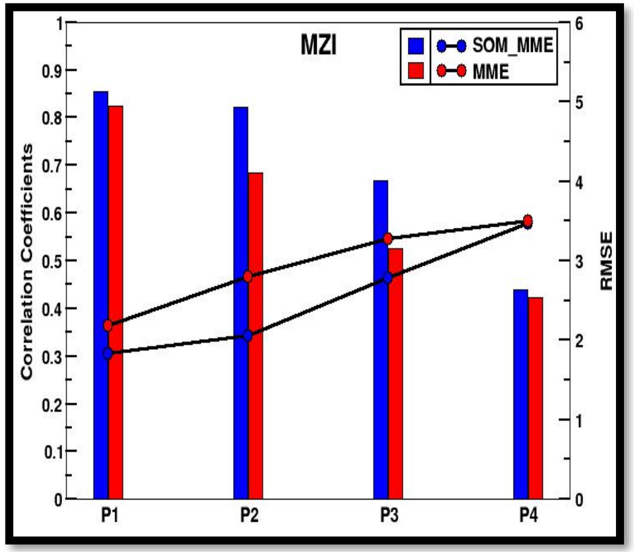
Task 6: Develop downscaling and bias correction techniques *



CC and RMSE



Brier Skill Score



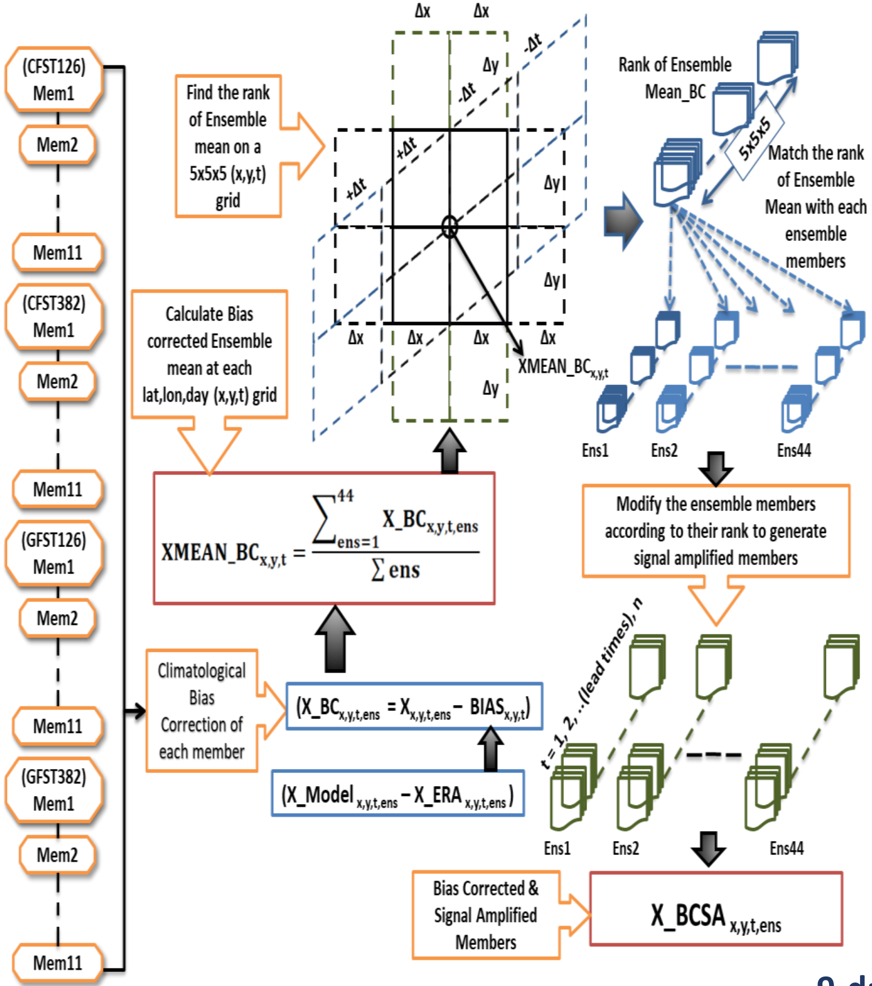
- **Downscaling of extended range forecast will help to disseminate the regional forecast.**
- **A Self Organizing Map based downscaling method is proposed. The hypothesis is that the large scale dynamical variables are captured better in the model.**
- **An empirical relationship between rainfall and dynamical model generated variables can be constructed based on which the rainfall estimate can be improved.**

Task 7: Develop signal amplification techniques*

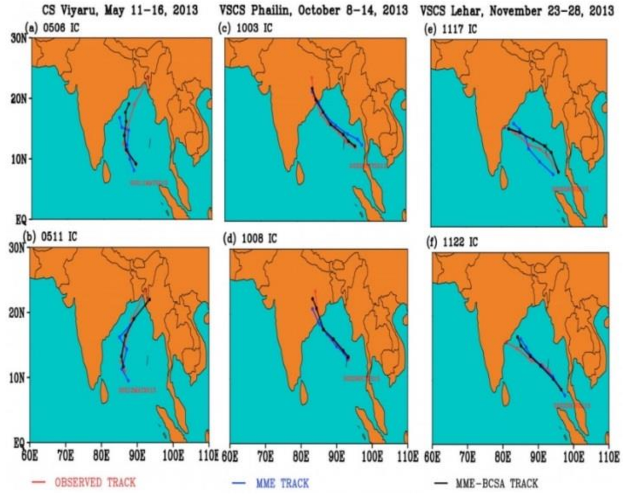
- **Bias-correction and signal amplification (BCSA) technique is, indeed, improving the track forecasts of selected cyclonic storm cases with significant reduction in track errors even at longer lead times.**

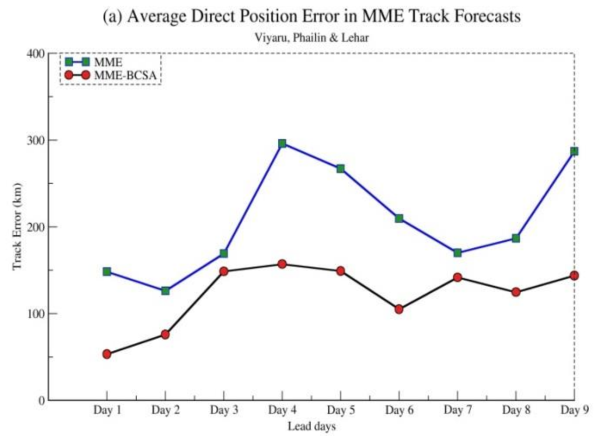
- **Track verification also shows that forecasts from MME-BCSA outperform MME for all lead days. A weakness of this method is that it considers ensemble mean as the signal and if signal is there, it can amplify it.**

- **Even then, BCSA is a unique postprocessing tool and computationally less expensive as it can be used on any number of already available MME outputs.**



Saranya Ganesh et al., GRL, April, 2018



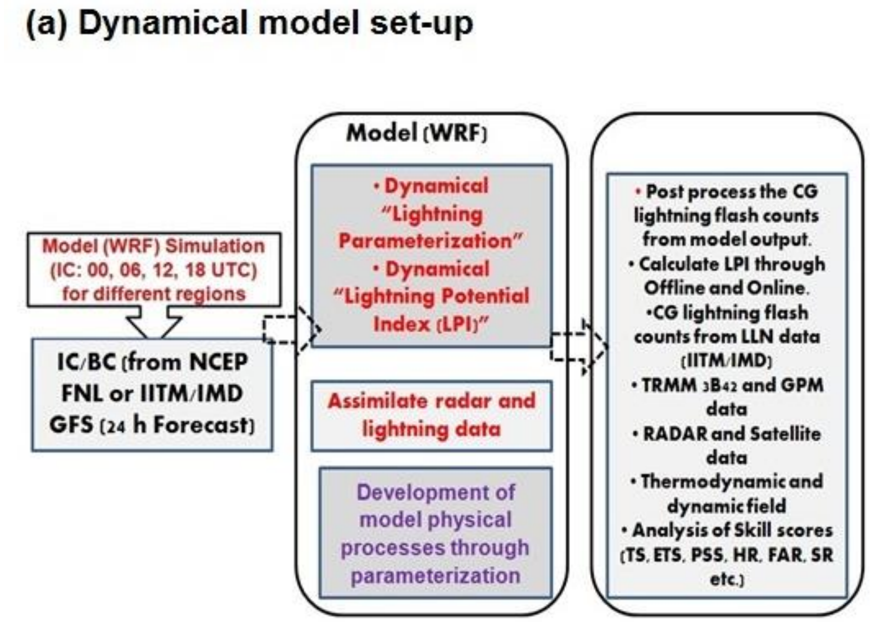


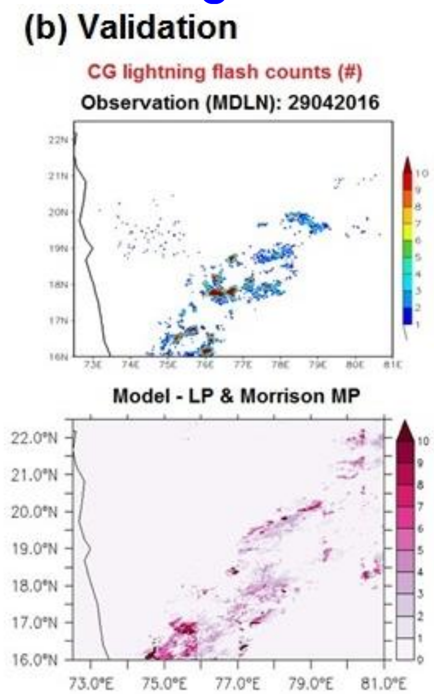
9-days average DPE- MME=206.7530834
9-days average DPE - BCSA= 97.5024516
Percentage of Improvement = 52.84 %

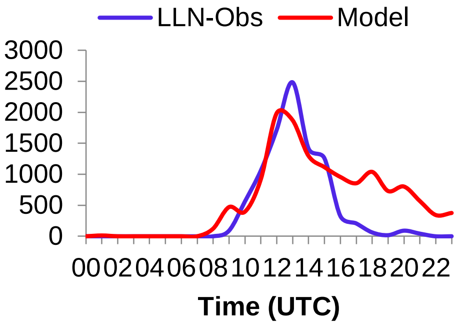
Objectives:

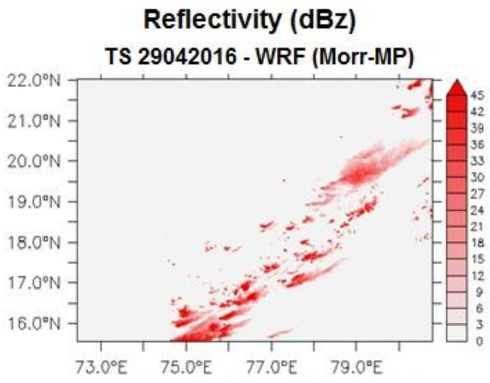
To develop a system for lightning/thunderstorm prediction using dynamical model

Proposed roadmap of thunderstorm nowcasting









Skill Score

Events	PSS	TS	ETS	HR	FAR	SR
TS (15)	0.65	0.51	0.39	0.85	0.19	0.56

*** Results presented in conference ICTLT2019, Bhubaneswar**

Skill Improvements due to Developmental Activities

	RUN (Ensembles)	Hindcast Period	Resolution	AISMR (GPCP), (% improvement over CTL)	Nino 3.4	IOD East Pole
(a)	**CONTROL (10)**	**2003-2017 (2016)**	**T126**	**0.33 (0.49, +9%)**	**0.53**	**0.70**
(b)*,#	**NCEP CTL (10)**	**2003-2017 (2016)**	**T126**	**0.42 (0.45)**	**0.57**	**0.76**
(d)#	**CFS-NCEP (10)**	**1981-2017**	**T126**	**0.29**	**0.53**	**0.58**
(d)	**COLA-CFS (10)**	**2003-2017**	**T126**	**0.60 (+81%)**	**0.61**	**0.62**
(e)	**SAS2 (10)**	**2003-2017**	**T126**	**0.54 (+63%)**	***0.70***	***0.81***
(f)	**SAS2sc (10)**	**2003-2017**	**T126**	**0.63 (+91%)**	**0.54**	**0.70**
(g)*,#	**NCEP SAS2 (10)**	**2003-2017**	**T126**	***0.70 (+67%)***	**0.66**	**0.67**
(h)*,#	NCEP SAS2sc (10)	2003-2017	T126	0.40 (-5%)	0.63	0.68
(i)#	**CFS-ALBEDO (10)**	**1982-2014**	**T126**	**0.11 (-56%)**	**0.64**	**0.31**
(k)	**INCOIS-T382 (14)**	**2003-2017**	**T382**	**0.47 (+42%)**	**0.49**	**0.67**
(k)#	**NCEP-T382 (10)**	**1981-2017**	**T382**	**0.51 (+76%)**	**0.53**	**0.54**
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(m)*,#	NCEP WSM6 (10)	1981-2012	T126	0.61 (+64%)	NA	NA
(n)*,#	CFS-ICE-Micro (16)	1981-2010	T126	0.70(+59%)	0.58	NA
(o)#	CFS-Hydrology (10)	1981-2017	T126	0.48 (+65%)	0.54	0.61

Runs carried out on Aditya indicated by *
All the runs are using INCOIS-NCMRWF initial conditions, unless indicated by #
Initialized with Feb. IC and skills are shown for JJAS

AISMR: All India Summer Monsoon Rainfall (Averaged over Indian Land Mass)

Core Time = 65 Years (567522 Hours)
T126 (6 Nodes: 9 months in 7 hours)
T382 (10 Nodes: 9 months in 40 hours)

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60-90% Improvement is achieved due to revised SAS of Han & Pan (2011)

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42-75% Improvement is achieved due to increased resolution

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T382 (10 Nodes: 9 months in 40 hours)

Skill Improvements due to Developmental Activities

	RUN (Ensembles)	Hindcast Period	Resolution	AISMR (GPCP), (% improvement over CTL)	Nino 3.4	IOD East Pole
(a)	CONTROL (10)	2003-2017 (2016)	T126	0.33 (0.49, +9%)	0.53	0.70
(b)*,#	NCEP CTL (10)	2003-2017 (2016)	T126	0.42 (0.45)	0.57	0.76
(d)#	**CFS-NCEP (10)**	**1981-2017**	**T126**	**0.29**	**0.53**	**0.58**
(d)	**COLA-CFS (10)**	**2003-2017**	**T126**	**0.60 (+81%)**	**0.61**	**0.62**
(e)	SAS2 (10)	2003-2017	T126	0.54 (+63%)	*0.70*	*0.81*
(f)	SAS2sc (10)	2003-2017	T126	0.63 (+91%)	0.54	0.70
(g)*,#	NCEP SAS2 (10)	2003-2017	T126	*0.70 (+67%)*	0.66	0.67
(h)*,#	NCEP SAS2sc (10)	2003-2017	T126	0.40 (-5%)	0.63	0.68
(i)#	**CFS-ALBEDO (10)**	**1982-2014**	**T126**	**0.11 (-56%)**	**0.64**	**0.31**
(k)	INCOIS-T382 (14)	2003-2017	T382	0.47 (+42%)	0.49	0.67
(k)#	NCEP-T382 (10)	1981-2017	T382	0.51 (+76%)	0.53	0.54
(l)*,#	NCEP Multi Cloud MP (10)	1982-2014	T126	0.45 (+7%)	0.58	0.43
(m)*,#	NCEP WSM6 (10)	1981-2012	T126	0.61 (+64%)	NA	NA
(n)*,#	CFS-ICE-Micro (16)	1981-2010	T126	0.70(+59%)	0.58	NA
(o)#	CFS-Hydrology (10)	1981-2017	T126	0.48 (+65%)	0.54	0.61

9% Improvement is achieved due to indigenous ICs

60-90% Improvement is achieved due to revised SAS of Han & Pan (2011)

42-75% Improvement is achieved due to increased resolution

60-65% Improvement is achieved due to In-house Developments (LSM, Microphysics, WSM6 and Hydrology)

Runs carried out on Aditya indicated by *
All the runs are using INCOIS-NCMRWF initial conditions, unless indicated by #
Initialized with Feb. IC and skills are shown for JJAS

AISMR: All India Summer Monsoon Rainfall (Averaged over Indian Land Mass)

Core Time = 65 Years (567522 Hours)
T126 (6 Nodes: 9 months in 7 hours)
T382 (10 Nodes: 9 months in 40 hours)

Improvement in seasonal prediction skill of ISMR due to in-house LSM & cloud microphysics development activities

A multilayer snow scheme (up to a maximum of six layers) is introduced in NOAH land model (SNOW)

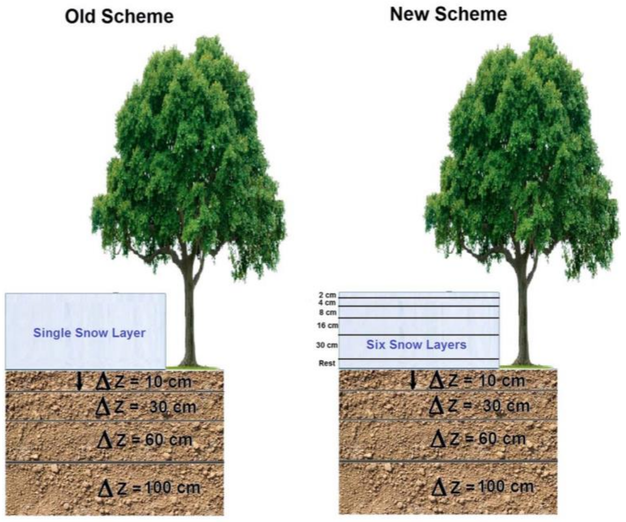


Figure 1. Schematic diagram of the snow and soil layers in the original and modified Noah.

Skill	IITM
CTL	0.56
New SNOW scheme	0.62
New microphysics scheme	0.71
SNOW+MPHY	0.63

New cloud microphysics scheme (MPHY)

Physical processes[b]	Experiment names: Control (CTL) run	Experiment names: Modified convective microphysics (MCM) with SAS (MCMv.1) run	Experiment names: Modified convective microphysics (MCM) with new SAS (MCMv.2) run
Convective process	Simplified Arakawa-Schubert (SAS) (Hong & Pan, 1998; Pan & Wu, 1995)	Modified original SAS of Pan and Wu (1995) and Hong and Pan (1998). The partitioning of cloud water and ice based on DeMott and Rogers (1990) and convective autoconversion as suggested by Wu et al. (2010). Detailed discussed in section 2 "Method."	Same as presented in MCMv.1, but modification carried out in new SAS (nSAS) of Han and Pan (2011).
Microphysics process	Ice and warm cloud-microphysics, cold rain followed by Zhao and Carr (1997) warn rain is based on Sundqvist et al. (1989).	Modified Ice and warm cloud-microphysics: Addition of snow accretion in cold rain in original Zhao and Carr (1997), Rain accretion is also added in warm rain. Autoconversion in warm rain of Sundqvist et al. (1989) is modified following Rotstayn (2000), based on CAIPEEX observation (Konwar et al., 2012; Kulkarni et al., 2012) by IITM. Details are presented in "Method" (section 2).	Same as presented in MCMv.1.

- The model is initialized on every 15, 20, and 25 February and 3 March (four cycles in a day, 00, 06, 12, and 18 GMT) for years 1981 to 2010 (30 years)
- 16-member ensemble simulations

Saha et al. (2017), Hazra et al. (2017), Saha et al. (2019)

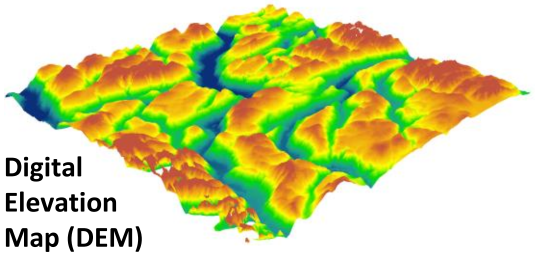
Coupling Hydrology Model to CFS

IITM CFS Model

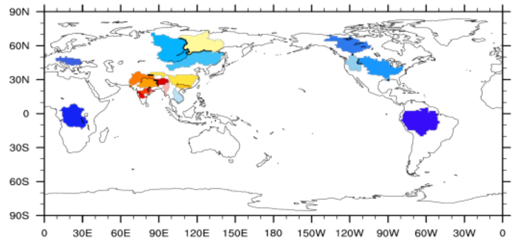
- T126 — Atmospheric Model GFS ← ATMOSPHERE INITIAL CONDITIONS
- Land Model NOAH | Ice Model
- 1 degree — RTM → Add RTM to pass runoff to MOM
- COUPLER
- Ocean Model MOMv4 global 1/2ºx1/2º (1/4º in tropics) 40 levels ← OCEAN INITIAL CONDITIONS

✓ **Closes the hydrological cycle**

The model is initialized on every 03, 05, 07 10, 12, 15, 17, 20, 22 and 25 February 00 UTC for years 1981 to 2010
10-member ensemble

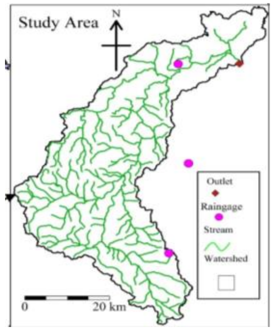


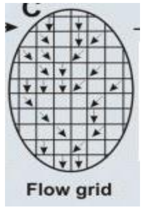
Digital Elevation Map (DEM)



Delineated River Basins (Global)

Flow Network

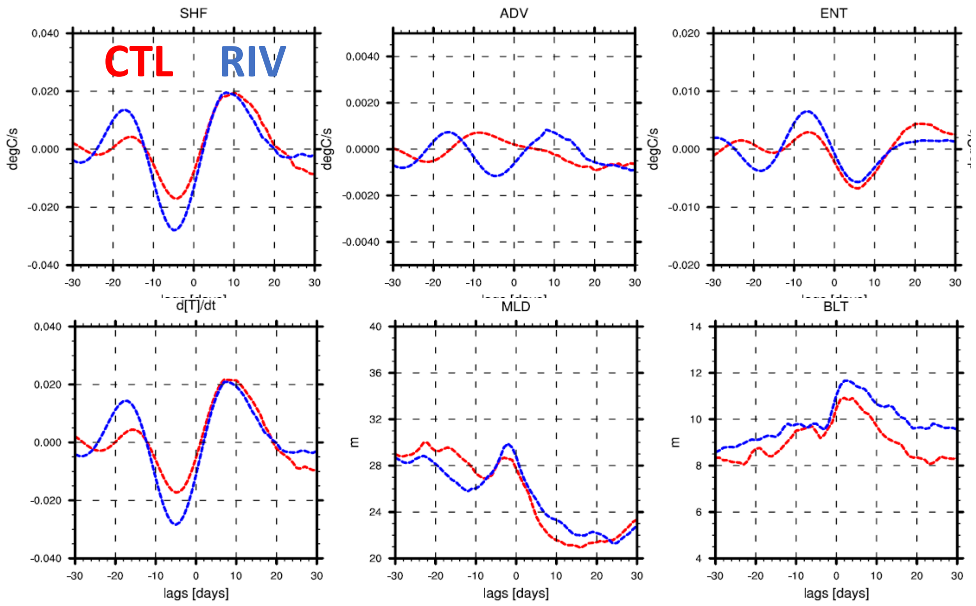




Runoff from land surface model

Routed streamflow at land-ocean boundaries

- ✓ Improved simulation of pre-convection warming and cooling during monsoon active phase.
- ✓ Improved simulation of mixed layer heat budgets and air-sea interactions at intra-seasonal time scales.
- ✓ Overall improvement in ISMR simulation skill.



Skill	1981-2017
CTL	0.39
RIV	0.48

Ankur et al., (2019, under preparation)

Future/Ongoing Activities

- Coupling of GFS(SL) with MoM 5.0 and MoM6.0 to prepare platform for seamless prediction
- Strongly Coupled Data assimilation system
- Hydrology coupled CFS with interactive fluxes
- New flux parametrization schemes implementation (e.g: wave-wind-current interactions)
- Implementation of Icosahedral dynamical core in CFS
- Implementing new version of Monsoon Mission model to be transferred to IMD
- GLDAS operationalization
- Continue with model developmental activities of convective parametrization, microphysics, land surface model (continuing activity)

IITM-ESM for long-term climate change studies

Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune

Atmosphere : GFS (Global Forecast System)

T62 ; vertical: 64 sigma – pressure hybrid levels

Resolution ~200 km

Model top 0.2 mb

Prescribed MAC-v2 aerosols

Land surface : Noah LSM

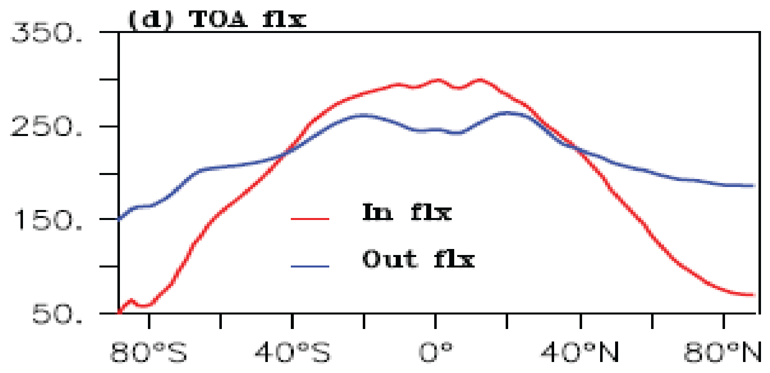
Ocean: Modular Ocean Model v4p1 (MOM4p1)

Tripolar; 360x200; 1 deg poleward; 0.33 deg near equator

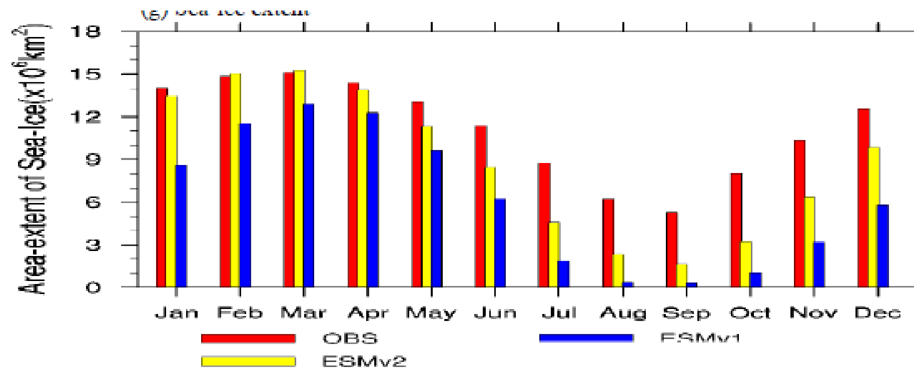
50 levels; Top grid cell 5m

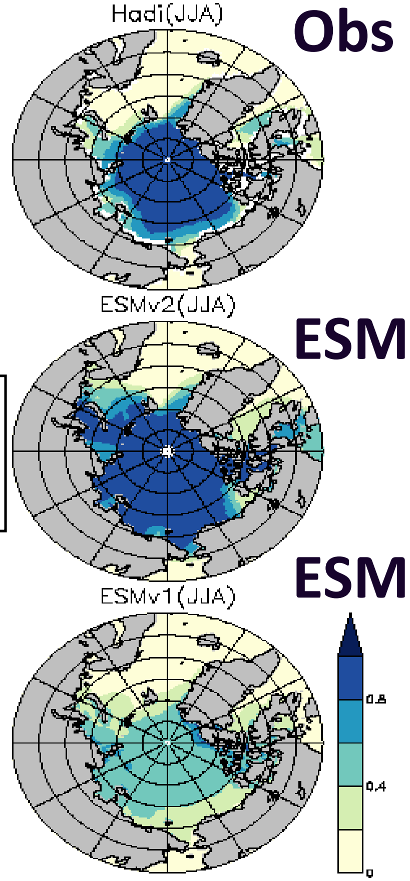
Ocean Biogeochemistry: TOPAZ

Ice Model: Sea Ice Simulator



Zonal mean annual mean components of TOA radiation balance with net heat gain in the tropical regions and a net loss at higher latitudes leading to a total imbalance of about 0.8 Wm-2





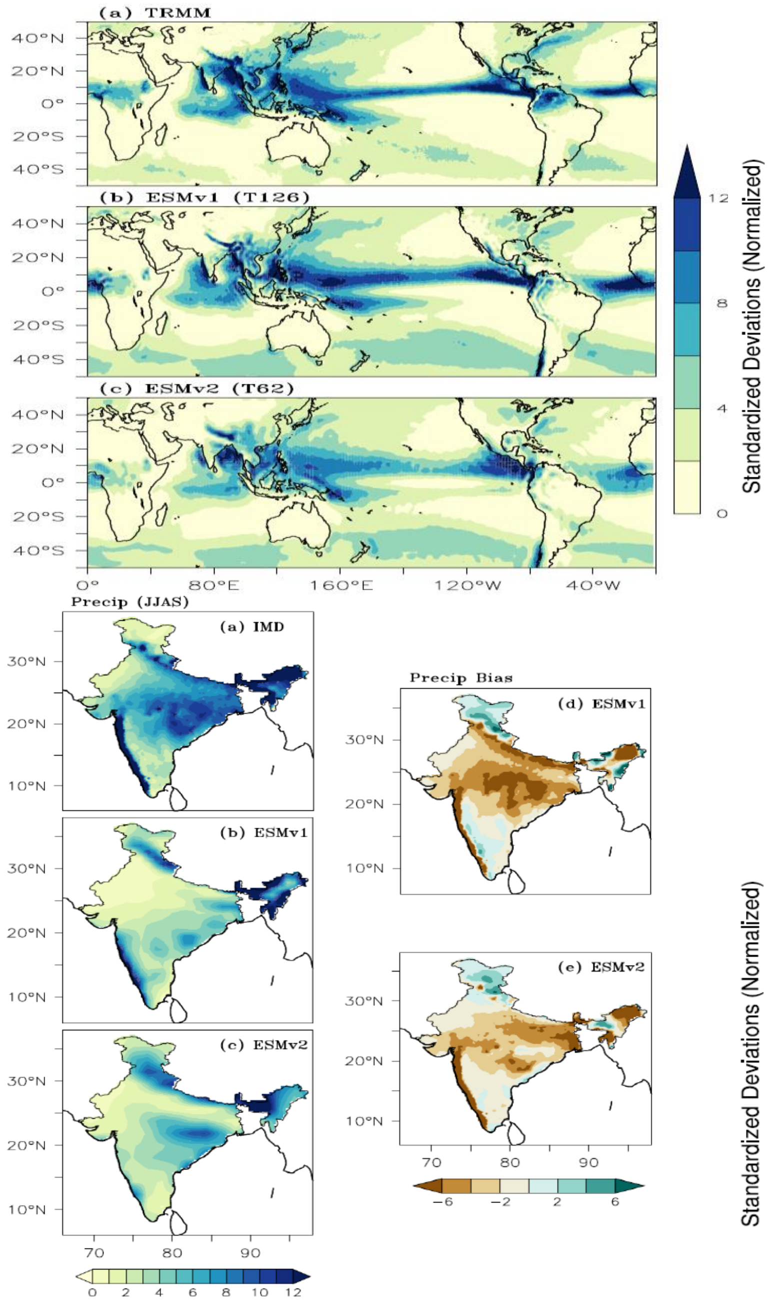
Obs

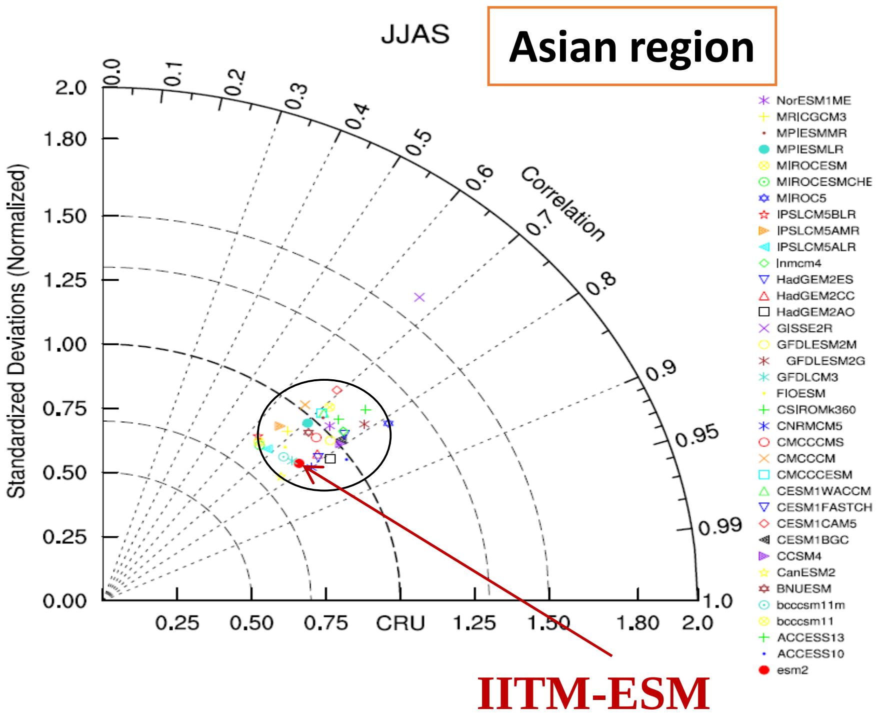
ESMv2

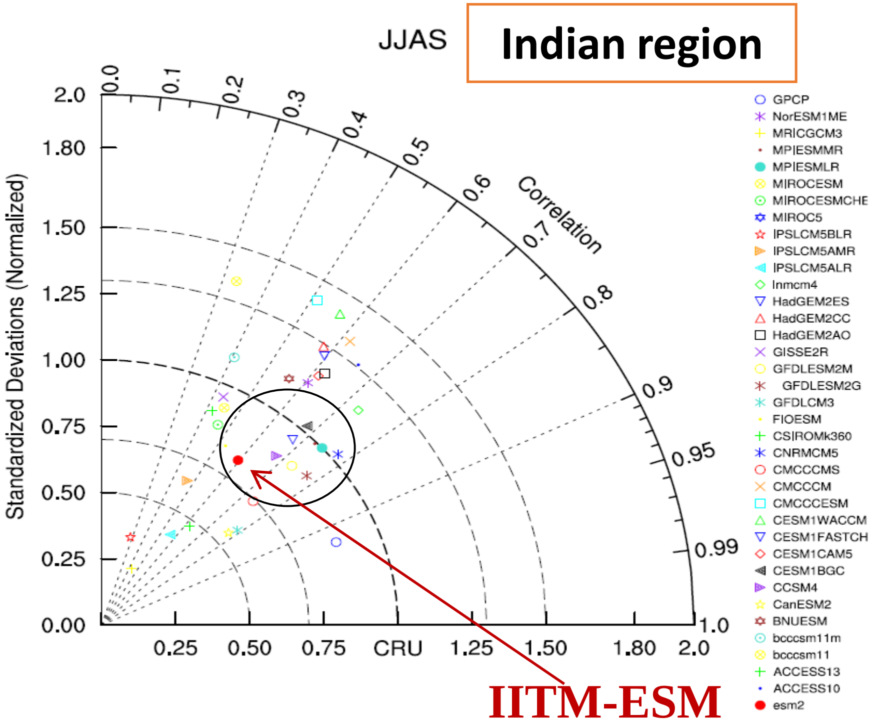
ESMv1

Improved simulation of NH sea-ice during JJA In ESMv2 over ESMv1

Mean summer rainfall (June-Sept)







Pattern correlation of mean summer monsoon rainfall (June-September) between the historical simulations of CMIP5 models, IITM-ESM and observation over south and southeast Asian (65°E-140°E, 10°S-45°N) domain (upper panel) and over Indian land region (lower panel).

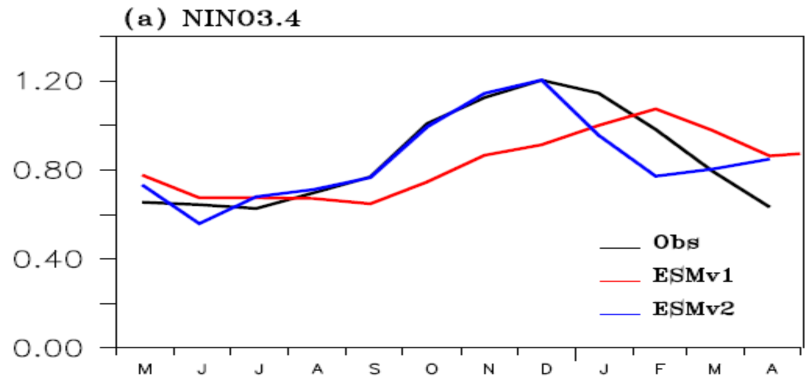
CMIP5 models are performing better over the bigger domain of south and southeast Asia in capturing the spatial pattern of mean seasonal rainfall, but many models have poor skill over the Indian region. IITM-ESM exhibits relatively better skill over Indian as well as Asian region .

Significant reduction in dry bias over Indian region in ESMv2 simulation as compared to ESMv1.

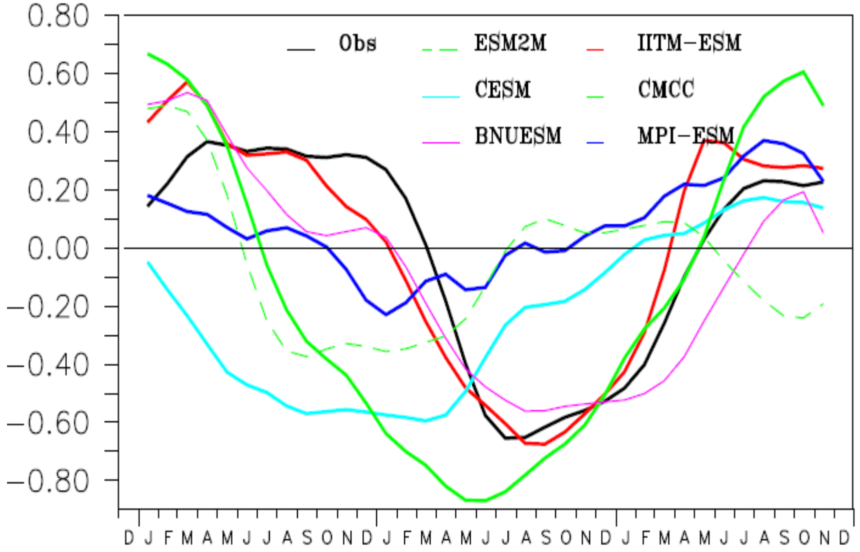
Inclusion of revised SAS schemes has reduced the rainfall bias in ESMv2 with a coarser resolution (T62) as compared to ESMv1 (T126).

Courtesy: Swapna

Seasonal variability of NINO3.4



ENSO-Monsoon teleconnection

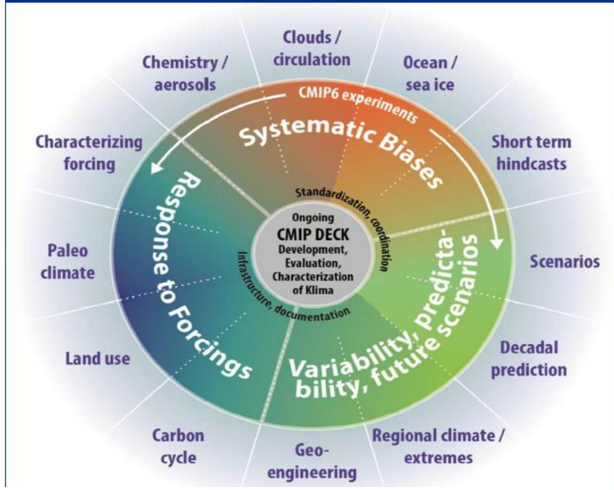


Seasonality of ENSO examined by analyzing the standard deviation of Nino 3.4 index from IITM-ESM simulations and observation

Lead-lag correlation between ISMR and NINO3.4 index from observation, CMIP5 models and IITM-ESM (red line). IITM-ESM captures the observed concurrent negative simultaneous correlations between monsoon and ENSO as well as lead-lag relationship.

CMIP6 Schematic: Participation in the 6th Intergovernmental Panel for Climate Change (IPCC)

Initial proposal for the CMIP6 experimental design has been released



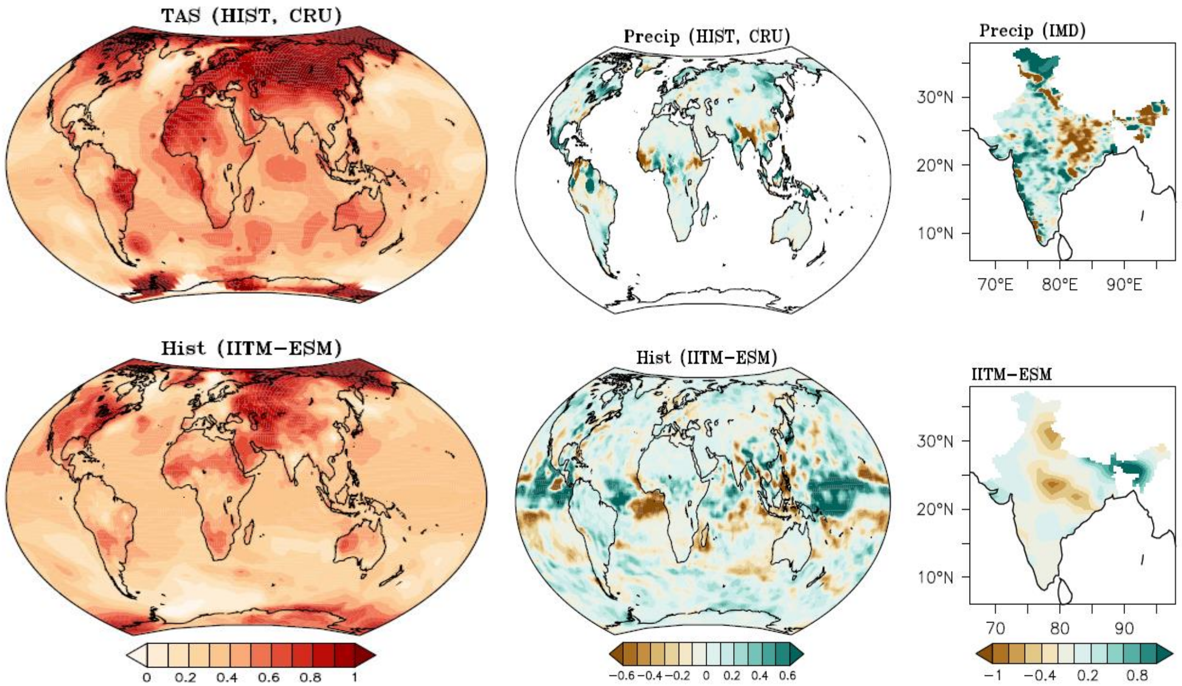
CMIP6 Concept: A Distributed Organization under the oversight of the CMIP Panel

IITM ESM will participate in the climate modeling CMIP6 experiments for the IPCC 6th Assessment Report

10

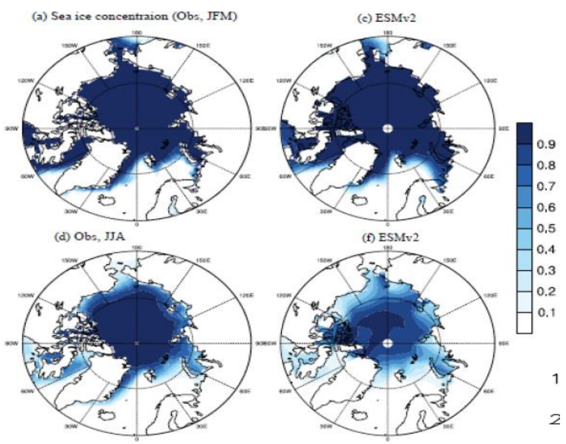
Spatial patterns of change in surface air temperature (°C) computed from trends during 1900-2014 **(a)** Observations **(b)** IITM-ESM (HIST)

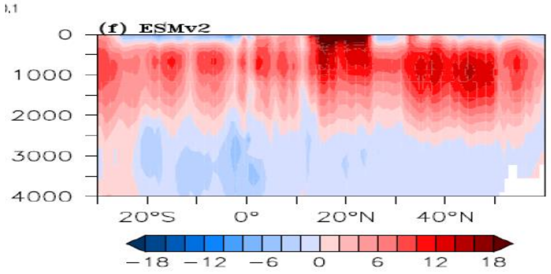
Spatial patterns of change in JJAS precipitation (mm day^{-1}) computed from trends during 1950-2014 **(a)** Observations **(b)** IITM-ESM (HIST)



Improved representation of Arctic sea-ice and AMOC in IITM-ESM.

Sea-ice concentration
IITM ESMv2





Atlantic meridional overturning circulation(AMOC)

Changes in spatial patterns of surface temperature and precipitation (JJAS) for the historical period (1900-2014) based on IITM-ESM historical simulation.

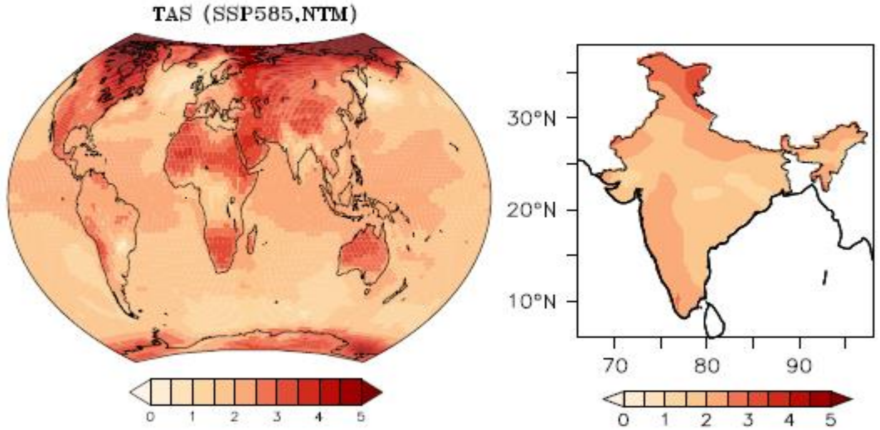
Increasing surface temperatures over most of the continental region with fastest warming over Arctic. The anthropogenic warming trend is reasonably well represented in IITM-ESM historical simulation.

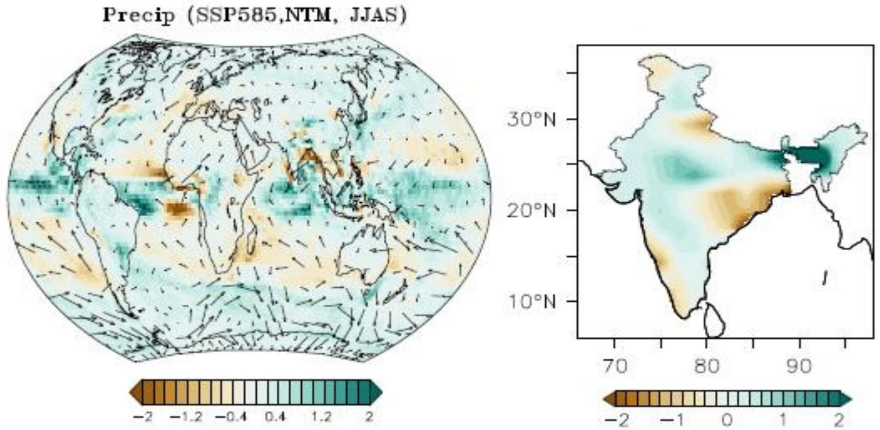
The precipitation pattern shows large spatial variability over the tropical regions. IITM-ESM captures the recent observed decline in the summer monsoon precipitation over central India and Peninsular Indian region

Courtesy: Swapna

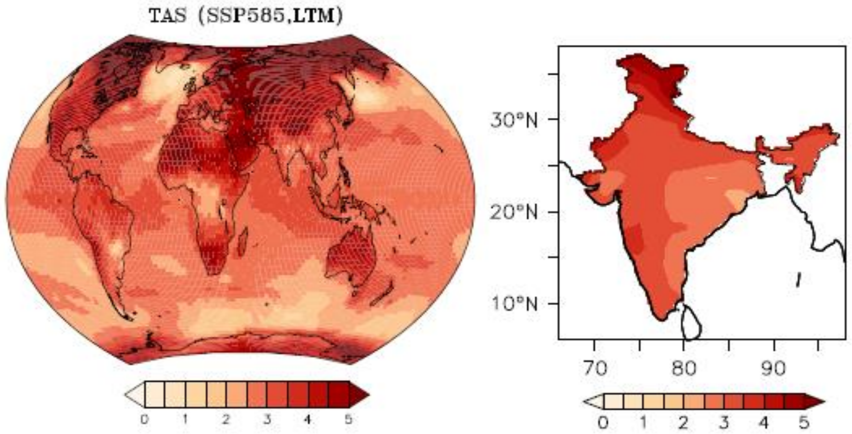
Surface temperature and precipitation response in IITM-ESM (SSP8.5) – CMIP6

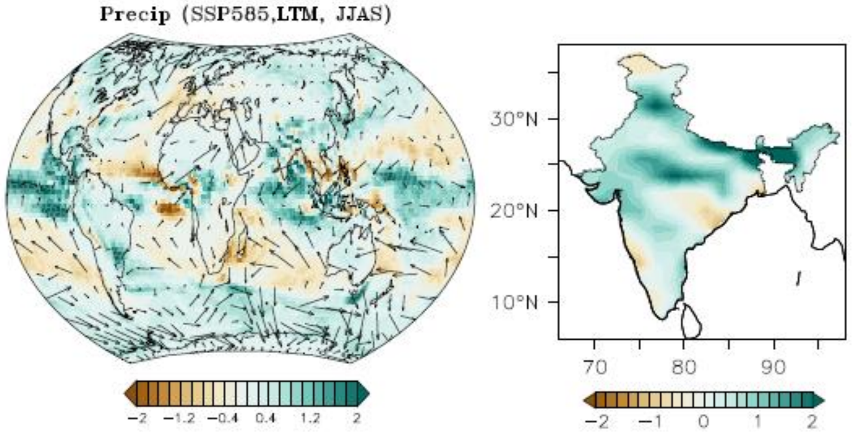
Near-term (2041-2069) minus PI-CTL (1850-1900)





Long-term (2071-2099) minus PI-CTL (1850-1900)





Changes in spatial patterns of surface temperature and precipitation (JJAS) for the near-term period (2041-2069) w.r.t pre-industrial period (1850-1900)

Changes in spatial patterns of surface temperature and precipitation (JJAS) for the long-term period (2071-2099) w.r.t pre-industrial period (1850-1900)

Courtesy: Swapna

THANK YOU

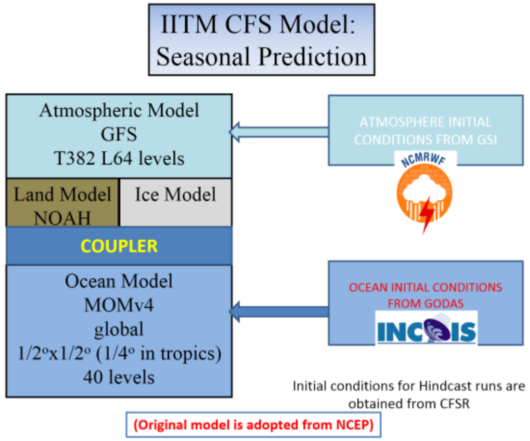
Any Questions?

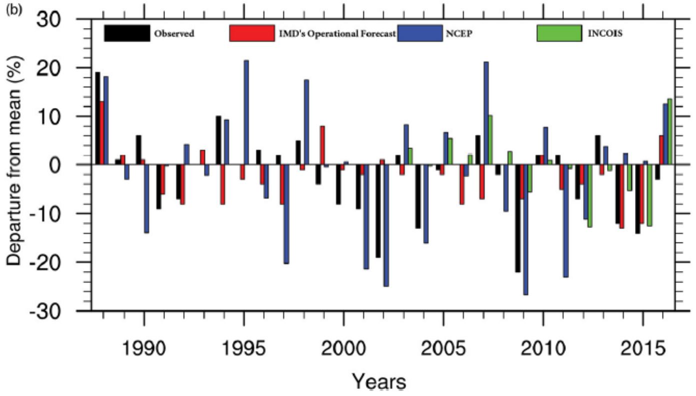
Extra Slides

MONSOON MISSION

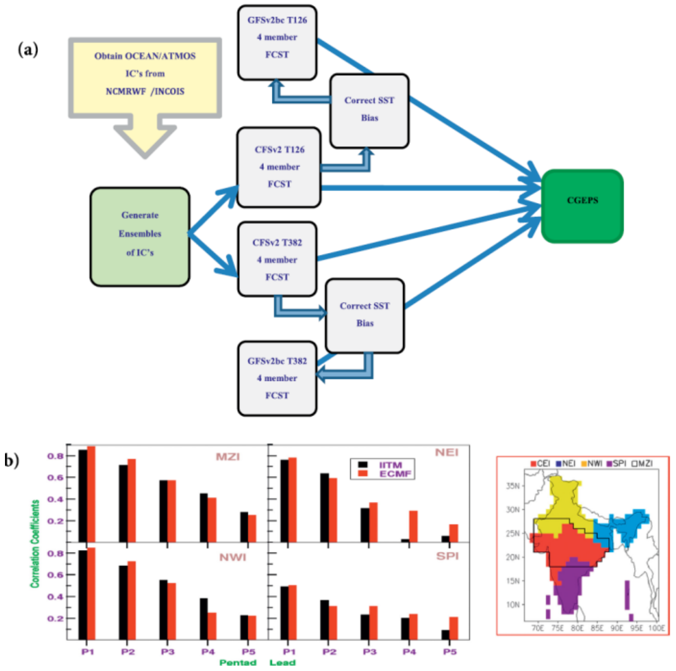
A Targeted Activity to Improve Monsoon Prediction across Scales

The Monsoon Mission is a national program that has nurtured a system to provide skillful Indian summer monsoon predictions, benefiting society and advancing global science.

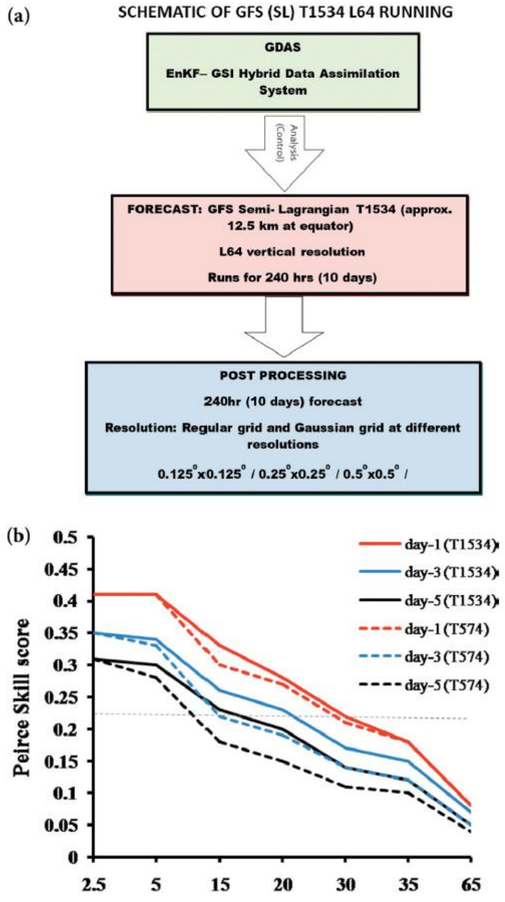




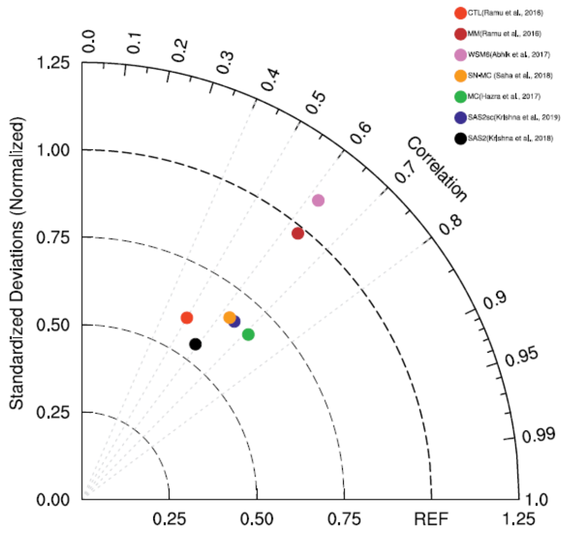
Unparalleled skill of 0.63 for seasonal prediction of the Indian monsoon (for the period 1981–2010) in a high-resolution (~38 km) seasonal prediction system



Extended-range predictions by a CFS-based grand multi-model ensemble (MME) prediction system

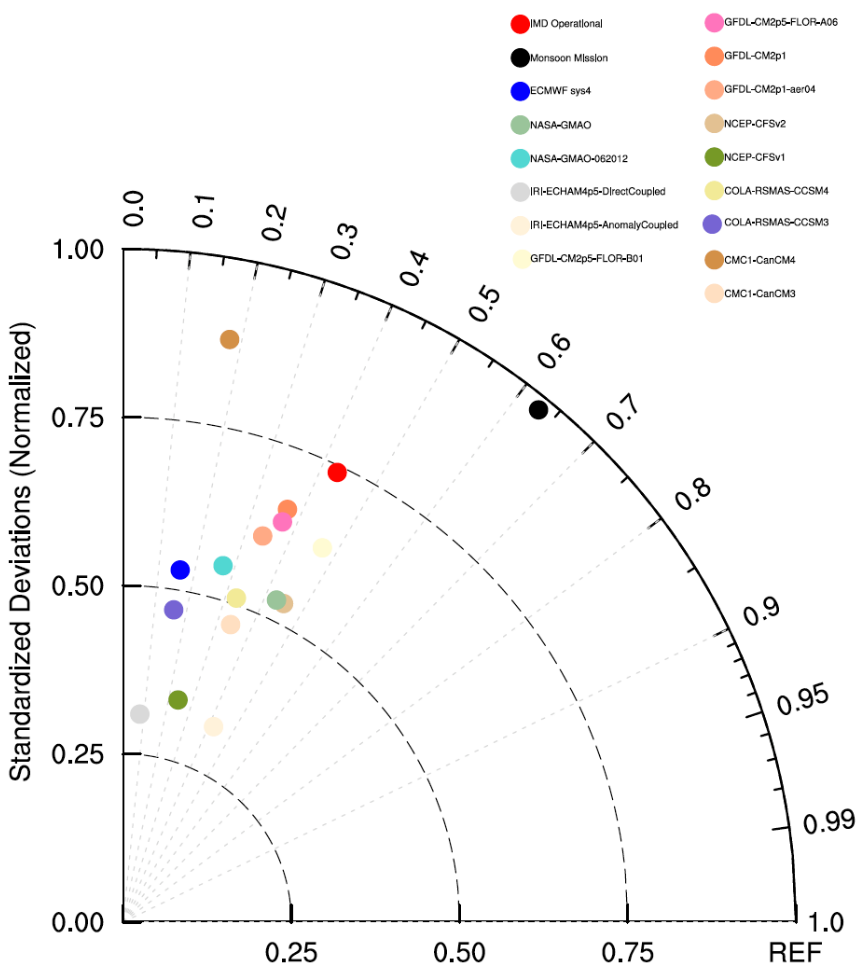


Very high-resolution (12.5 km) Global Forecast System (GFS)-based short range predictions up to 10 days



Model developmental activities

Improvement in seasonal prediction skill of ISMR due to indigenous ICs



Pillai et al., (2019)

ACC (2003-2016)	IITM	IMD	GPCP
Monsoon Report	0.96	0.89	0.92
INCOIS	0.56	0.40	0.49
NCEP	0.43	0.47	0.45

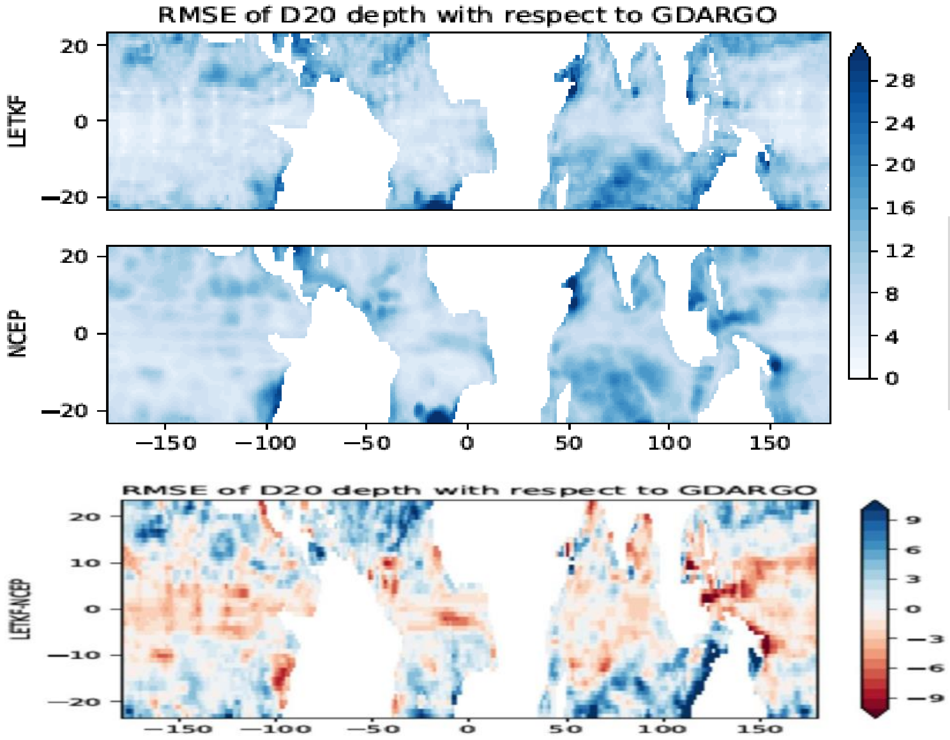
ACC (2003-2017)	IITM	IMD	GPCP
Monsoon Report	0.95	0.89	0.91
INCOIS	0.47	0.26	0.47
NCEP	0.45	0.46	0.47

- It has been identified that quality of ocean ICs had gone bad since 2017. INCOIS confirmed that the data buoys after 2016 November are were not assimilated into the analysis due to switching over to NCMRWF GTS data and TAC to bufr.
- The issue is being rectified.

Weakly Coupled Data Assimilation System

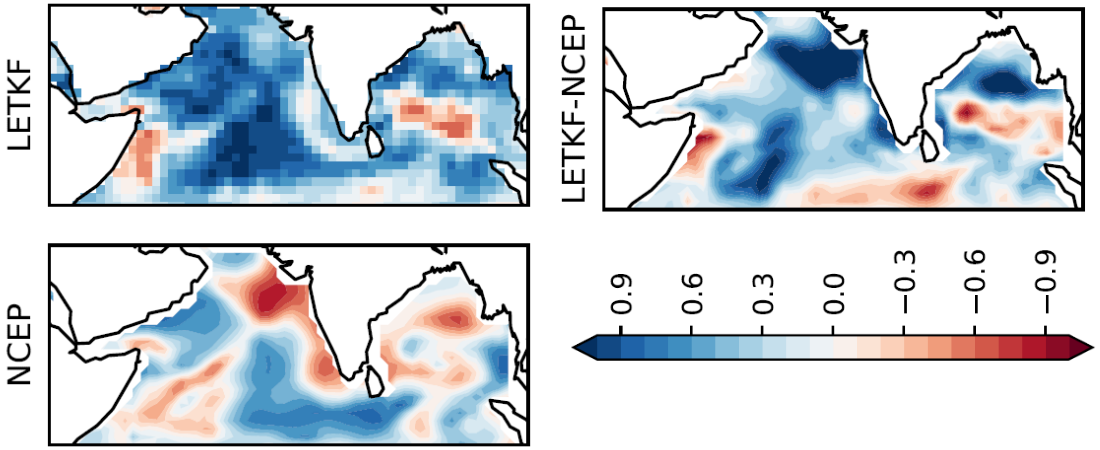
	WCDA LETKF
Resolution	~108 km (T126) with 64 levels. ocean 0.25° at the equator, extending 0.5° beyond the tropics
Coupling	Coupling of atmosphere and ocean during the generation of the 9 hour guess field
Ocean Data Assimilation	MOM - LETKF
Atmosphere Data Assimilation	GFS – LETKF
Limitations	Assimilation scheme is flow dependent for both atmosphere and ocean Ocean-atmosphere interactions are not used directly. Rather the information is used for background information. The actual reanalysis is uncoupled.
Observations assimilated	Conventional ocean and atmospheric profiles

RMSE of D20 in WCDA



Improvements can be seen everywhere.

JJAS corr_coeff of sal at depth 5m

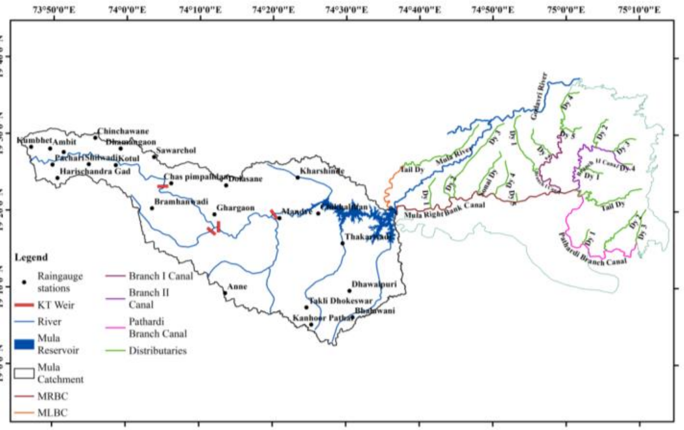


Correlations are Positive in WCDA, while negative correlations are evident in AS in NCEP CFS-R

Saha et al., (2010), Sluka et al., 2016

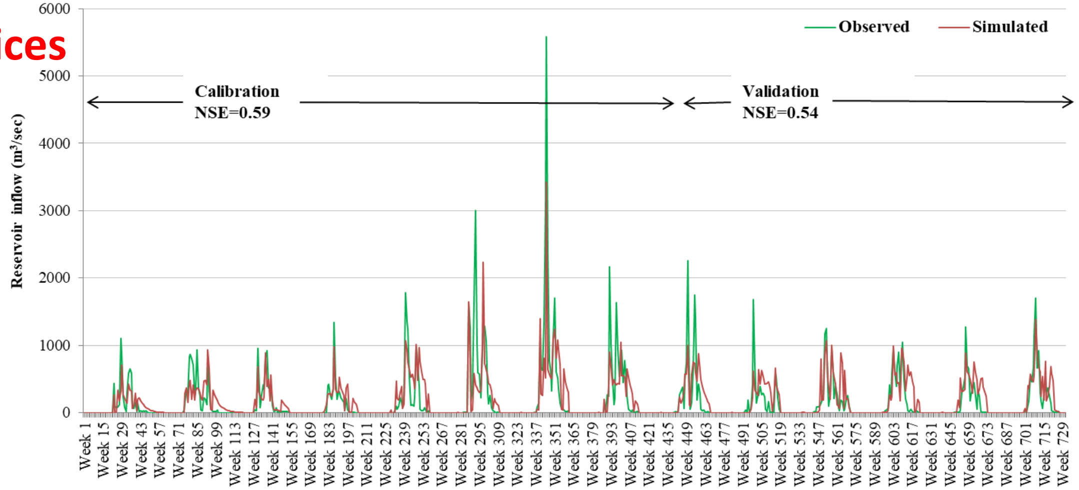
Hydrology applications

Usability of Climate information for Reservoir Management Practices

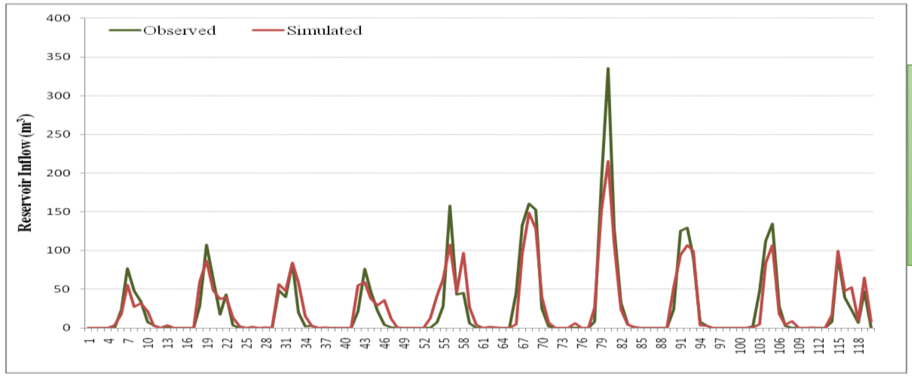


The meteorological data is obtained from CFS seasonal prediction runs.

Reservoir Inflow Weekly analysis

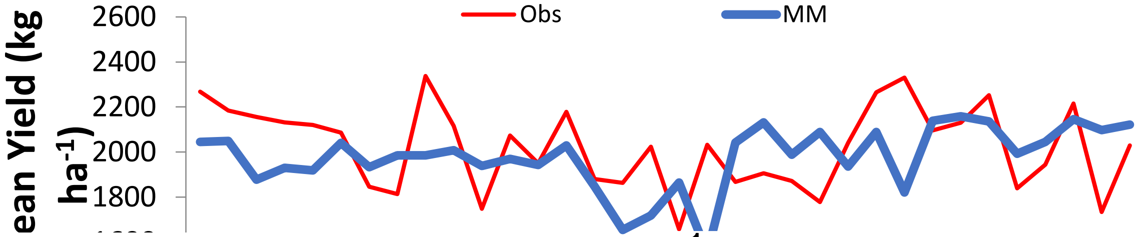


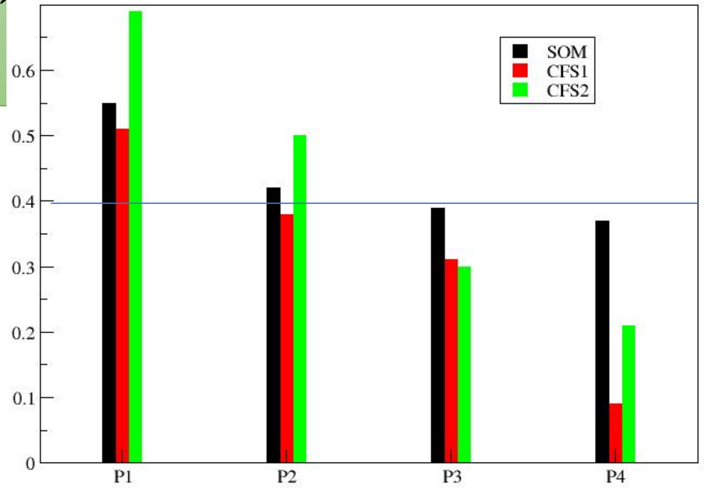
Reservoir Inflow Monthly analysis

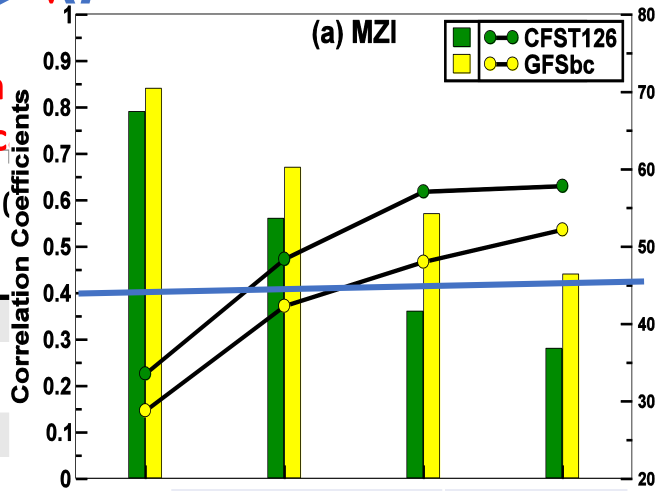


NSE=0.68 (Very Good)
PBIAS=14 (Good)

Performance rating	NSE	PBIAS (%)
Very good	0.75<NSE < 1.00	PBIAS < ±10
Good	0.65<NSE<0.75	±10<PBIAS<±15
Satisfactory	0.50<NSE<0.65	±15<PBIAS<±25
Unsatisfactory	NSE <0.50	PBIAS>±25







Thus input/output post processing or ensemble techniques provides an improved skill and it took only one year to implement

Skill Improvements due to Developmental Activities

	RUN (Ensembles)	Hindcast Period	Resolution	AISMR (GPCP), (% improvement over CTL)	Nino 3.4	IOD East Pole
(a)	CONTROL (10)	2003-2017 (2016)	T126	0.33 (0.49, +9%)	0.53	0.70
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(m)*,#	NCEP WSM6 (10)	1981-2012	T126	0.61 (+64%)	NA	NA
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9% Improvement is achieved due to indigenous ICs

60-90% Improvement is achieved due to revised SAS of Han & Pan (2011)

42-75% Improvement is achieved due to increased resolution

60-65% Improvement is achieved due to In-house Developments (LSM, Microphysics, WSM6 and Hydrology)

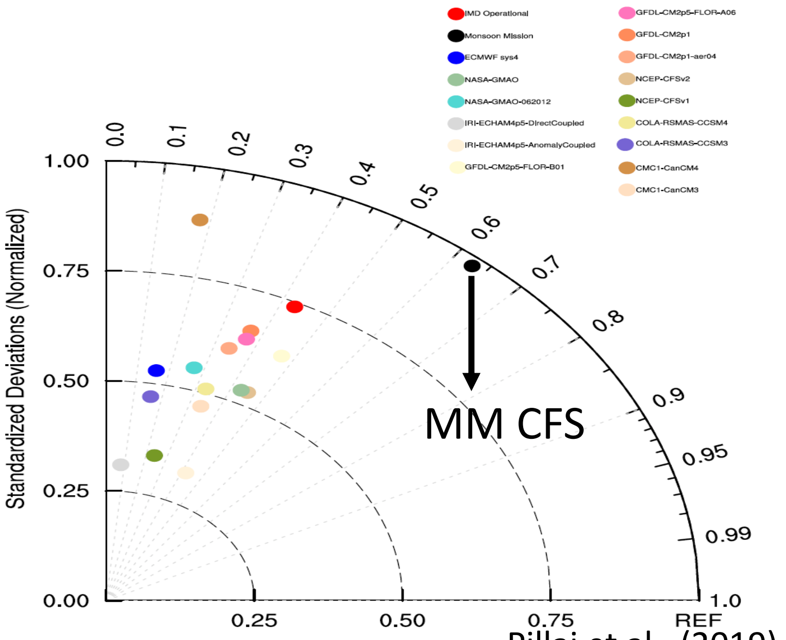
Runs carried out on Aditya indicated by *
All the runs are using INCOIS-NCMRWF initial conditions, unless indicated by #
Initialized with Feb. IC and skills are shown for JJAS

AISMR: All India Summer Monsoon Rainfall (Averaged over Indian Land Mass)

Core Time = 65 Years (567522 Hours)
T126 (6 Nodes: 9 months in 7 hours)
T382 (10 Nodes: 9 months in 40 hours)

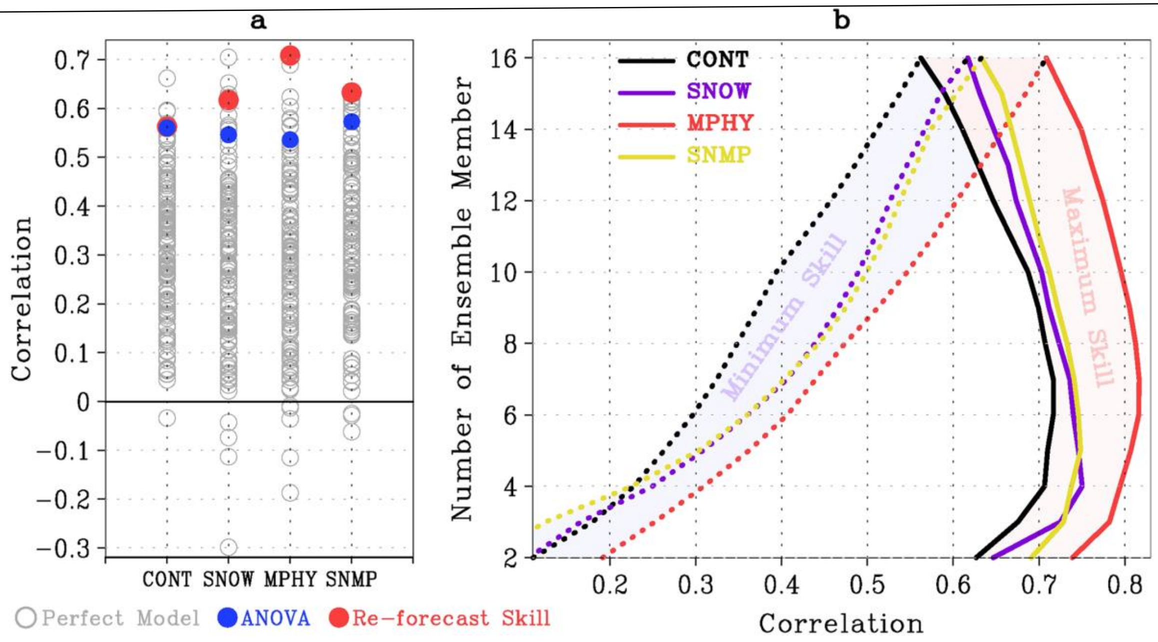
Improvement in seasonal prediction skill of ISMR due to indigenous ICs

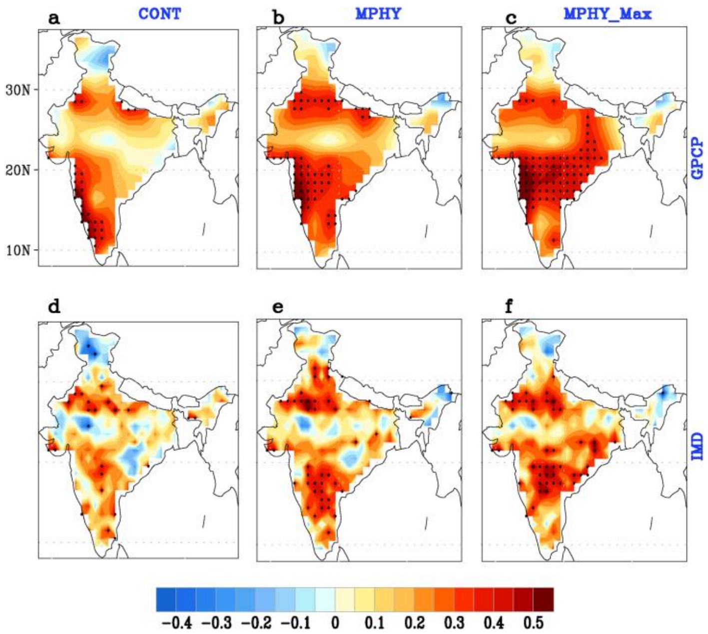
ACC (2003-2016)	IITM	IMD	GPCP
Monsoon Report	0.96	0.89	0.92
INCOIS	0.56	0.40	0.49
NCEP	0.43	0.47	0.45



Pillai et al., (2019)

Improvement in seasonal prediction skill of ISMR due to in-house LSM & cloud microphysics development activities

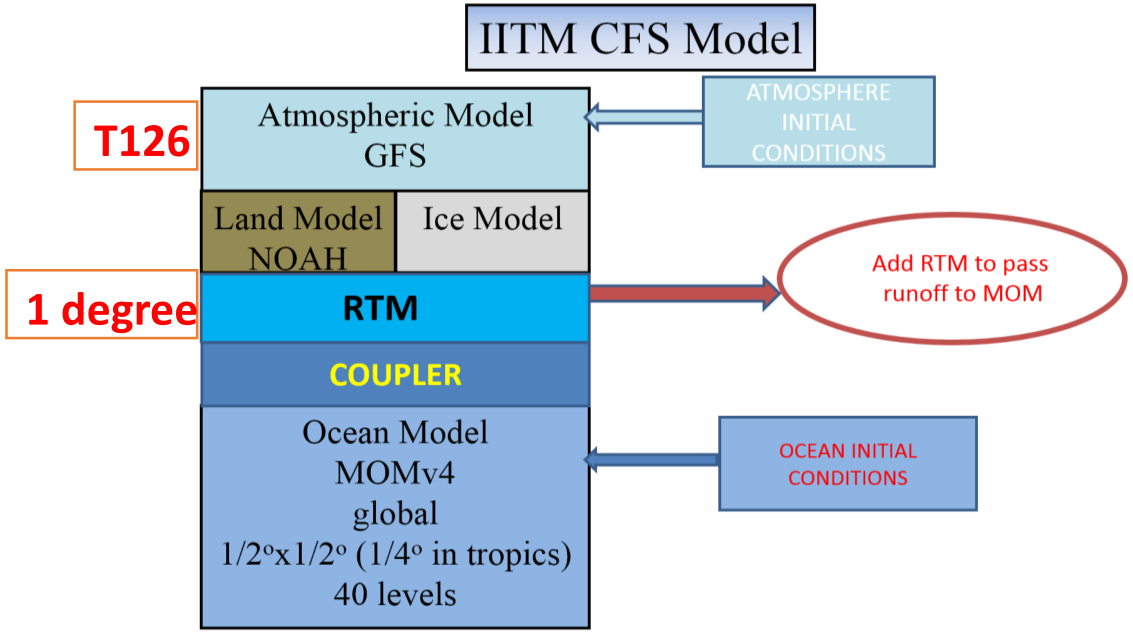


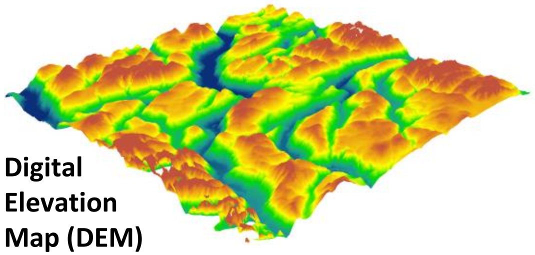


Unraveling the Mystery of Indian Summer Monsoon Prediction: Improved Estimate of Predictability Limit

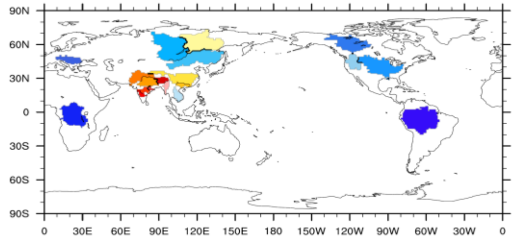
Journal of Geophysical Research: Atmospheres, First published: 06 February 2019, DOI: (10.1029/2018JD030082)

Coupling Hydrology Model to CFS



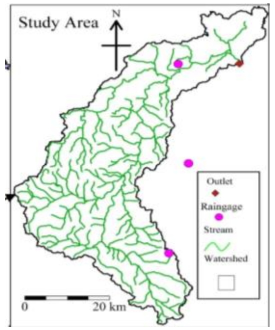


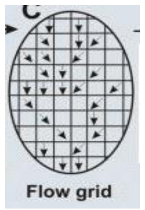
Digital Elevation Map (DEM)



Delineated River Basins (Global)

Flow Network

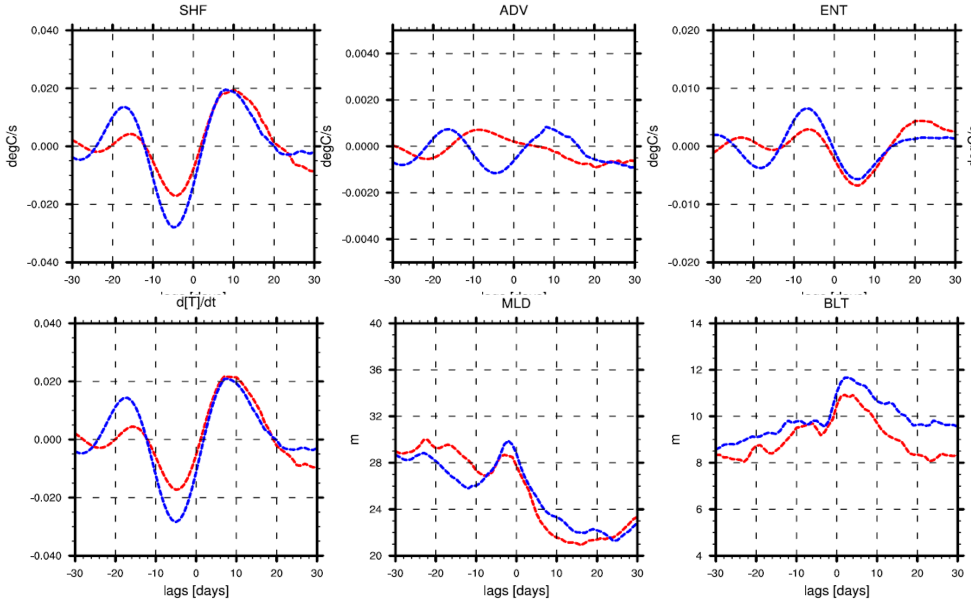


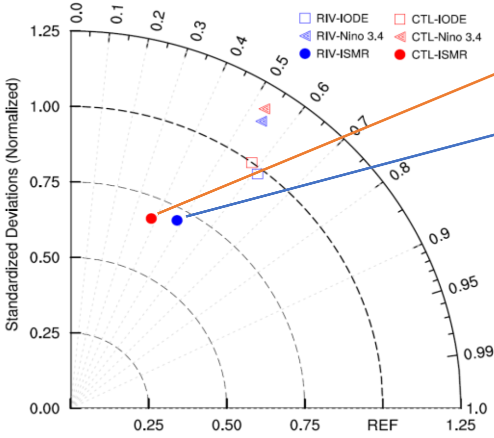


Runoff from land surface model

Routed streamflow at land-ocean boundaries

Improved simulation of mixed layer heat budgets and air-sea interactions at intra-seasonal time scales





CTL run, ACC=0.39

RIV run, ACC=0.48

An improvement in AISMR skill

Ankur et al., (2019, under preparation)