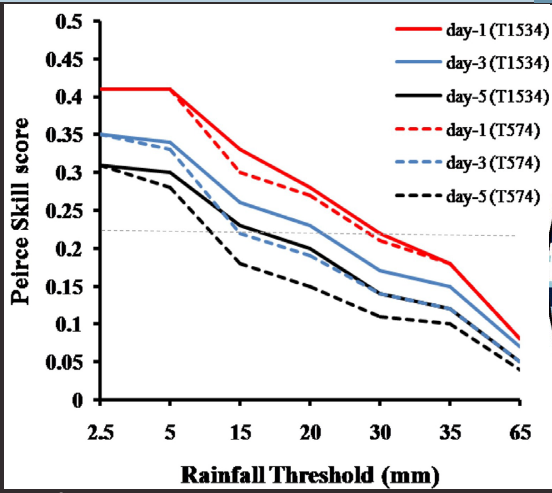
ISSN 0252-1075
TECHNICAL REPORT No.TR-05
ESSO/IITM/MM/TR/01(2020)/198

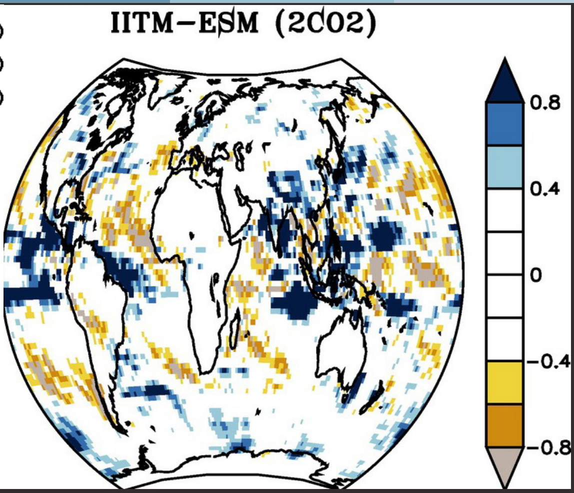
ROADMAP FOR IITM MODEL DEVELOPMENT

Towards Seamless Prediction of Monsoon weather and climate

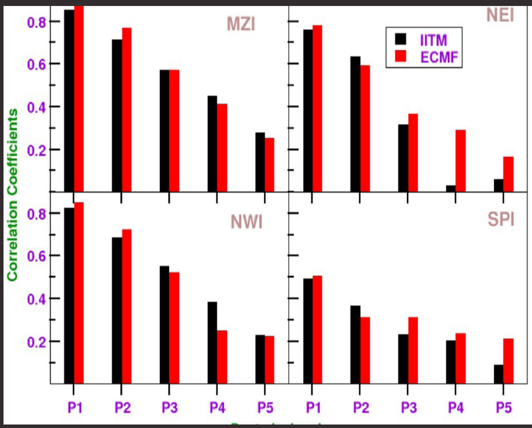
2020 - 2029



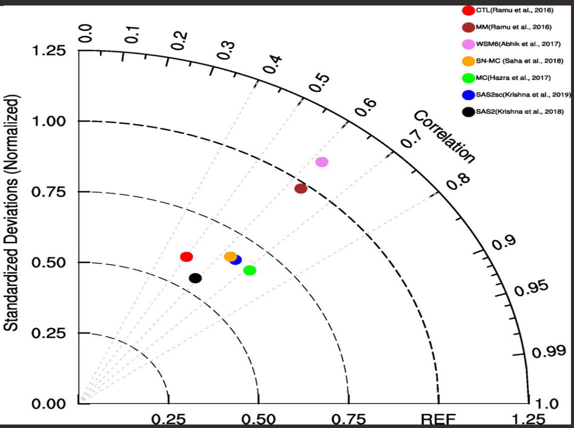
Gain of 2 days Forecast at Short range time scales



India's first Earth system model simulation with 2xco2



Prediction of Active/Break Cycles of Monsoon



Development of world's best seasonal prediction system for Monsoon forecasting

FEBRUARY 2020

Description of Figures on Cover Page

Top left figure: Forecast skill (Peirce skill score) for different rainfall threshold values for day 1, day 3, and day 5 forecast of GFS system of MM for different resolutions (T1534 and T574).

Bottom left figure: Pentad 1 (P1) to pentad 5 (P5) forecast skill of IITM extended-range prediction system and ECMWF operational system for different homogenous regions of India: the monsoon zone of India (MZI), northeast India (NEI), northwest India (NWI), and south peninsular India (SPI).

Top right figure: Spatial map of summer monsoon (JJAS) precipitation (mm day–1) anomalies in 2 × CO2 experiment from IITM-ESM.

Bottom right figure: Taylor diagram showing the skill of ISMR prediction using reforecasts from the control run (CTL) and the developmental activities under MM, namely, the revised microphysics (WSM6) along with revised convection (SAS2) and a modified radia-tion scheme, new cloud physics parameterization (MC), the new snow model (SN) and MC together (SN-MC), the revised convection parameterization scheme (SAS2), and SAS2 with a revised shallow convection scheme (SAS2sc). The improvement in skill over the CTL run is notable in the experiments. The period of the hindcast is 1981–2010.

Suggested Citation:

Roadmap to IITM model development towards seamless prediction of monsoon weather and climate, IITM Technical Report, ISSN 0252-1075, *ESSO/IITM/MM/TR/01(2020)/198*, February 2020.

https://www.tropmet.res.in/~lip/Publication/Technical-Reports/TR-5.pdf

ISSN 0252-1075
Contribution from IITM
Technical Report No.TR-05
ESSO/IITM/MM/TR/01(2020)/198

ROADMAP FOR IITM MODEL DEVELOPMENT

Towards Seamless Prediction of Monsoon Weather and Climate
2020-2029

-- by--
Modeling Groups at IITM

Corresponding E-mail: lip@tropmet.res.in
Phone: +91-(0)20-25904311

Indian Institute of Tropical Meteorology (IITM)
Ministry of Earth Sciences (MoES)
PUNE, INDIA
http://www.tropmet.res.in/

DOCUMENT CONTROL SHEET

Ministry of Earth Sciences (MoES)
Indian Institute of Tropical Meteorology (IITM)

ESSO Document Number
ESSO/IITM/MM/TR/01(2020)/198

Title of the Report
Roadmap for IITM Model Development: Towards Seamless Prediction of Monsoon Weather and Climate - 2020-2029

Authors
Modeling Groups at IITM

Type of Document
Technical Report

Number of pages and figures
47, 4

Number of references
98

Keywords
Model Development Roadmap, Short-range forecast, Extended range forecast, Seasonal forecast, Climate change projections

Security classification
Open

Distribution
Unrestricted

Date of Publication
February 2020

Executive Summary
One of the major objectives of IITM is to provide essential R&D services to the India Meteorological Department to improve the skill of their operational forecasts. The institute activities are always orchestrated in this direction and also this document. Encouraged by the results in the last ten years, particularly in model development, we have ventured into designing a roadmap for IITM model development to be taken up in the next ten years. The primary goal of this roadmap is to develop a unified modelling framework for delivering seamless predictions of monsoon weather and climate. This outcome will be achieved by following a systematic approach to addressing various modelling issues noticed in the last ten years and initiating new strategies particularly in the dynamical core, data assimilation techniques and adding earth system modules in addition to improving the model physics.

Table of Contents

FOREWORD

Indian Institute of Tropical Meteorology started in November 1962, with an original mandate to provide basic R&D services to India Meteorological Department to improve the skill of their operational forecasts. To fulfill this mandate, Forecasting Research Division was setup in April 1963. While interactions occurred between IMD and IITM in various areas, major technology transfer that gave a quantum change to IMD's forecasting capabilities occurred in mid-2010s, when models developed under the Monsoon Mission were operationalized by IMD.

About eight years ago, the Monsoon Mission was launched to improve monsoon forecasts at all scales i.e. short, medium and seasonal scales using dynamical models. It was an ambitious and comprehensive mission mode programme to build dynamical forecast systems across these scales. Its objective was also to engage and interact with research and academic institutions worldwide so as to have the best-in-class forecast systems for monsoon predictions. Indian Institute of Tropical Meteorology was the nodal implementing agency for this mission. Till the launch of this programme, dynamical modeling was confined to few pockets within the country and seasonal predictions of monsoons were almost entirely based on statistical prediction techniques. The major successes of this mission are

(i) a seasonal prediction system based on a dynamical coupled model with very good skill for monsoons(perhaps the best) at a high resolution of 37km

(ii) a state-of-art multi-model ensemble system for extended range for predicting active-break cycles of monsoons, heatwavesetc

(iii) a global ensemble forecast system for short-range with the highest resolution (12 km). All these achievements were possible due to the dedicated work done by the scientists of IITM in close collaboration with various institutes worldwide.

These forecasting systems were handed over to India Meteorological Department and have been used by them with a remarkable degree of success. This success is a major motivating factor for us, the scientists at IITM.

In parallel, an Earth System Model (IITM-ESM) was also developed at the Centre for Climate Change Research of IITM. This model is now participating in CMIP6 and will contribute significantly to the next IPCC report.

Research has been conducted at IITM on almost every aspect for forecasting viz. data assimilation (to create very good initial conditions for both oceans and atmosphere) improvements in modeling especially on its weakest link i.e. prescription of clouds and its properties. The remarkable strides made by IITM in gaining expertise in modeling and data assimilation has been recognized by experts worldwide. Hence a comprehensive roadmap taking into account the requirements of IMD and also leveraging the expertise available within IITM was felt to be necessary. The Research Advisory Committee of IITM, comprising of experts from IMD, NCMRWF, IISc,etcand also from outside the country, while commending the work being done at IITM also felt that such a roadmap would be useful. The contents of this document were reviewed by the RAC twice in successive years.

The document gives a view of future plans, taking into account the requirements of IMD, the expertise available at IITM and gaps in expertise that need to be filled. We propose to continue working on

(i) cloud parameterization – where new techniques such as stochastic parameterization and scale-aware techniques will be used in conjunction with data from observations gathered by IITM for improving the prescription of clouds;

(ii) data assimilation – some work has been done in the field of weakly coupled data assimilation in collaboration with University of Maryland, this would be taken further - a strongly coupled data assimilation technique based on Ensemble Kalman Filters is proposed;
(iii) We are also working on other aspects of model physics such as land surface parameterization
(iv) A new feature being added to our coupled dynamical forecast system is incorporation of river runoff and hydrology in an interactive fashion – our model is one of the few seasonal forecast system to boast of this.
(v) We propose to initiate work on boundary layer modeling and radiation parameterization.

A new area where the expertise is almost absent is in the development of dynamical cores. To fill this gap, a two-pronged strategy has been adopted. Cubic octahedral formulation will be used for a new dynamical core. This is a strategy that is also in the plans of ECMWF. Additionally an icosahedral based dynamical core is being developed in collaboration with IIT Kanpur and Japanese scientists.
We also propose to experiment with the use of emerging techniques such as AI/ML, embedding them inside the model and also for offline improvements. Also these models are computationally intensive. In the last decade, IITM has emerged as the biggest HPC centre in the country. All the developments in forecasting would not have been possible but for HPC infrastructure which has been generously supported by MoES. Today it boasts of the country's largest supercomputer. It is necessary to recast our modeling framework to exploit computational technologies in an efficient fashion. We are initiating work on code improvements and optimization on various emergent platforms.

In short, what we are planning is a complete evolution of the current model based on CFS/GFS to a truly Indian model. Additionally we are also looking at application of the forecasts in various domains such as hydrology, agro-meteorology, renewable energy etc.

Today IITM's modeling has come of age. Our research has led to considerable improvements in quality of forecasts. The same is being recognized by researchers within the country and abroad. They have shown their willingness to work as equal partners in the endeavor to improve monsoon forecasts. Hence it is imperative that we have a comprehensive view of our modeling strategy in the form of a roadmap. Major modelling groups of the institute contributed to this report . This document is not one that is frozen but that which would evolve based on requirements of the country and developments in research around the globe. This document would be a useful guide for us to channelize our research. Achieving the goals mentioned in this document would be a dream-come-true for us at IITM.

I would like to thank Ministry of Earth Sciences for its generous support but for which all this would not be possible. All the work done at IITM is completely supported by MoES. I am particularly thankful to DrRajeevan, Secretary MoES, for his constant support, advice and encouragement. I am grateful to all my predecessors who nurtured this institute and laid foundations for the successes that we are witnessing today. Last but not the least, I am thankful to all my colleagues at IITM who have made our institute a grand success story.

Director,
Indian Institute of Tropical Meteorology,
Pune, India

ACHIEVEMENTS 2010-19

Quantum leap in modelling and its development

1. From standalone low-resolution atmospheric modelling to state-of-the-art coupled modelling system comprising of coupled models and standalone models (12.5 km ensemble prediction system for short range forecasts, 38 km extended and seasonal forecasts and ~ 100 km climate projections).
2. Lead time for reliable short range forecasts increased by 2 days (from 3 to 5 days).
3. Reliable extended range predictions are provided up to 3 weeks lead time.
4. Seasonal predictions of monsoon with unprecedented skill of 0.6 with 3 months lead.
5. First Earth System model from India is developed that is participating in CMIP6/ IPCC AR6.
6. Setup of air-quality, thunderstorm and fog forecasting systems with reliable forecasts with 24 hour lead time.

Model Development

1. High resolution models
2. Ensemble prediction
3. Convective parametrization (super, stochastic and deterministic)
4. Cloud microphysics
5. Land surface parametrization
6. Addition of aerosols and ocean bio-geo-chemistry
7. Improved TKE parameterization

Applications

1. Heat/Cold wave forecast at extended and seasonal time scales
2. Agriculture practices using, seasonal and extended range predictions
3. Identification of hotspots of forest fires
4. Wind/solar energy
5. Health

HOW WAS IT POSSIBLE?

1. Existing senior scientists were supported by providing additional manpower.
2. More than 10 scientists with modelling experience were inducted.
3. Upgradation of HPC system from sub TF to multiple PF (~ 4PF).
4. Financial support in terms of focused research programs of MoES (Monsoon Mission, CCCR, SAFAR etc.).
5. Support from international centers like NCEP and other universities.

BOTTLENECKS

1. Development work carried out in pockets and less coordination among different groups.
2. Modelling and observational groups' interaction was very limited.
3. Model development/modification research in some modules was not initiated (e.g. boundary layer, radiation, sea-ice, ocean mixing and coupling).
4. HPC resources and additional limited manpower.

The major Goal of this document is to set achievable targets for next 10 years in development of a next generation coupled seamless prediction system with unified modelling framework for making weather and climate predictions/projections.

ROADMAP OF MODEL DEVELOPMENT

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Data Assimilation	Operationalization of weakly Coupled data assimilation system	Setting up of strongly coupled data assimilation system		Operationalization of strongly coupled DA		Development of strongly coupled hybrid LETKF system			Final DA System	
	Operationalization of Land Data Assimilation System	Hindcast experiments of short, extended and long range forecasts with weakly coupled DA		Hindcast experiments of short, extended and long range forecasts with strongly coupled DA						
Dynamical Core	Operationalization of TCO GFS and CFS	Experiments with Icosahedral Grid		Hydrostatic/non-hydrostatic dynamical core		Setting up a CFS model based on improved and scalable dynamical core				
Parametrization and new modules	Modification of stochastic parametrization schemes and scale aware parametrization schemes by constraining them with relevant observations	Addition of Modules (Ocean waves, interactive river routing module and new LSM,)		Development of advanced physics package based on the research/modifications carried out so far			Continue addition of Modules (Ocean waves, interactive river routing module and new LSM, new flux parametrization scheme)		Final physics package	
	Changing Coupler	Modification of stochastic parametrization schemes and scale aware parametrization schemes. Use of AI/ML techniques					Modification of stochastic parametrization schemes and scale aware parametrization schemes			
	Initiation of work on coupled NWP									
Final Outcome	Initial setup of Framework of seamless prediction system	Operationalization of first version of seamless prediction system at IMD New ESM model version based on above modifications				Next Generation Unified modelling framework for making Seamless prediction system				

SUMMARY

At present, IITM is engaged in following major modelling activities

1. Climate Projections (100s of years)
2. Seasonal Predictions (9 months)
3. Extended Range Predictions (4 week)
4. Short Range Predictions of Weather (10 days)

For all the above prediction/projection activities, IITM would like to develop a high resolution coupled framework from weather scale to climate scale with improved physics (emphasis on stochastic and scale aware parameterization), dynamics and also by including different components of the earth system. IITM realizes that it is imperative to constantly improve the data assimilations system to improve weather and climate predictions and IITM will strive to develop state of the art strongly coupled data assimilation system.

The models to be developed over the next decade will be used for the following:

1. The climate projections at 25 km resolution globally.
2. Decadal prediction of monsoon at 100km resolution.
3. The seasonal prediction at 25 km resolution.
4. Extended range prediction at 25 km resolution.
5. The weather prediction at 6 km resolution.

The above development would be an advancement from the existing 150 km resolution of IITM ESM to 25 km global IITM ESM. From 38 km resolution seasonal and extended prediction to 25 km and from 12.5 km

> Global seamless coupled modelling system from days to centuries with highest resolution.

to 6 km for 10 days weather prediction using global coupled weather prediction system.

In achieving the above goals, the developments that have taken place in physical parameterization, dynamical cores etc. at IITM and under monsoon mission, will be integrated in the modelling system. Using data from IITM observational campaigns and field experiments, existing parameterization schemes will be constrained in making them more suitable for the region.

Ocean bio-geochemistry, interactive aerosols, river routing with interactive coupled hydrology, ocean waves etc. will be added to the present coupled model system.

The target would be to achieve the following:

1. More reliable climate projections with improved regional details.
2. Seasonal prediction with higher skill over homogeneous regions of India.
3. Higher skill of Extended range prediction for 3rd and 4th week.
4. Anomaly correlation of 0.7 for seven days forecast and better skill in capturing the extreme precipitation events.

MODEL DEVELOPMENT ACTIVITIES

IITM is engaged in the development of state-of-the-art prediction systems for tropical weather and climate in the scale of short range weather, extended range prediction, seasonal prediction and climate projection.

The modelling systems developed so far, have been successfully transferred to India Meteorological Department for enhancing the operational forecasting capability of the country.

The present document provides the roadmap for a seamless model development to be accomplished by 2025 in the mentioned scales (short, extended, seasonal, decadal and climate) mostly with indigenous resources and systems and utilizing more Indian data in the assimilation as well as in improving the model parameterizations.

The development that will be achieved through this endeavor, will be transfered to IMD for making operational forecasts with improved skill and quality of the services to society at all space and time scales.

The next generation IITM NWP Model is planned to be seamless in predicting/simulating short range weather, weekly weather, seasonal prediction, decadal and climate projections.

Current scenario of modelling systems at IITM

The short range forecast has been developed in deterministic and ensemble based probabilistic forecast (with 21 ensemble members) at 12.5 km horizontal resolution globally.

The extended range prediction system provides probabilistic prediction up to 4 weeks taking 11 members each from GFST126 (horizontal resolution ~110 km), GFST382 (horizontal resolution~38 km), CFST126 (horizontal resolution~110 km) and CFST382 (horizontal resolution~38 km). The grand ensemble of the forecast from the four models is used to generate the extended range prediction products.

The seasonal forecast system is being run every month for next 9 months with 45 ensemble members to generate dynamical monsoon forecast over the country at 38 km resolution.

The IITM Earth System Model (IITM ESM) has been used for the first time in the IPCC CMIP6 and the indigenously developed IITM ESM projections have been published in ESGF grid along with other global models. The resolution at which the IITM ESM has been run is T62 horizontal resolution of ~210 km.

The following development would be taken up towards the development of next generation IITM model.

New dynamical core (GFS, CFS and IITM ESM)

Several non-hydrostatic models are now in use, having been largely developed in the past 10-20 years in response to exponential growth in computing power. Major non-hydrostatic models include the UK Met Office unified model (Davies et al., 2005; Staniforth and Wood, 2008), the Non-hydrostatic Icosahedral Atmospheric Model (NICAM), which was developed by Tomita and Satoh (2004), the NOAA Non-hydrostatic Icosahedral Model (Govett et al., 2010, NIM) and the Ocean-Land Atmosphere model (OLAM) (Walko and Avissar , 2008). Recently, GFDL has also developed a non-hydrostatic dynamical core on the cubed-sphere (Putman and Lin, 2009) based on the work of Putman and Lin (2007). These models all make use of some sort of conservative finite difference or finite-volume formulation to ensure conservation of mass and adopt the Arakawa C-grid staggering (Arakawa and Lamb, 1977). Other non-hydrostatic models include the ECMWF model IFS (Wedi et al., 2013) which makes use of the spectral transform method, and the semi-Lagrangian Canadian GEM model (Yeh et al., 2002).

(RLL) grid, (including the UK Met office model), it is well known that the RLL grid suffers from convergence of grid lines at the north and south poles. As a consequence, models using the RLL grid require the use of polar filters to remove instabilities associated with small grid elements, which can in turn severely damage performance on parallel systems. Many recently developed hydrostatic and non-hydrostatic models have tended away from this grid, instead using quasi-uniform grids such as the icosahedral or cubed-sphere grids. Several hydrostatic models are now built on the icosahedral grid. Non-hydrostatic models that use the icosahedral grid include NICAM, NIM and OLAM. The icosahedral grid has been shown to perform well on large parallel systems, but the non-Cartesian structure of the grid leads to difficulties in organizing the grid within memory. Another choice of quasi-uniform grid is the cubed-sphere grid, which was originally developed by Sadourny (1972) and revived by Ronchi et al. (1996). It was later used as the basis for a shallow-water model by Rancic et al. (1996). Since then, shallow-water models have been developed using the cubed-sphere grid that utilize finite-volume methods (Rossmanith, 2006; Ullrich et al., 2010), multi-moment finite-volume (Chen and Xiao, 2008), the discontinuous Galerkin

The spectral element method was successfully extended to a full hydrostatic atmospheric model (the Spectral Element Atmosphere Model, SEAM)

(Fournier et al., 2004), which is part of the High-Order Method Modeling Environment (HOMME). HOMME incorporates both the spectral element and discontinuous Galerkin methods, and has proven to scale efficiently to hundreds of thousands of processors. More recently, the GFDL finite-volume dynamical core has been modified to use a cubed sphere grid (Putman and Lin, 2007), and also has been demonstrated to be very effective at high resolutions.

In India, work on dynamical cores is completely lacking. In an atempt to rectify this lacuna it is proposed to create some expertise in developing dynamical cores and associated numerical methods. This would be done in two steps

1. use a new but existing dynamical core, and
2. develop a new dynamical core.

Cubic Octahedral Grid Framework

As the GFS/GEFS T 1534 modelling system is based on linear Gaussian grid with triangular truncation in the spectral domain, many challenges are being faced particularly in scaling the model in High Performance Computing (HPC) systems, the I/O issue, spectral truncation in Gaussian linear grid requires artificial damping of diffusion and even though the semi-lagrangian dynamical core allows larger time step to make the forecast run faster.

To get rid of the above mentioned issues related to dynamical core of a high resolution model, a Spectral Cubic Octahedral (TCo) framework has been planned for which developmental work has already been initiated to incorporate this grid into GFS.

TCo grid efficiently handles all the issues mentioned above without any compromise in the forecast accuracy. It may be worthy to mention that all the ECMWF modeling systems are based on TCo framework. Figure 1 demonstrates the steps of making the TCo grid.

> Enhanced grid resolution would help to achieve better skill for extreme precipitation events by resolving complex topographies.
> e.g. The Western Ghat

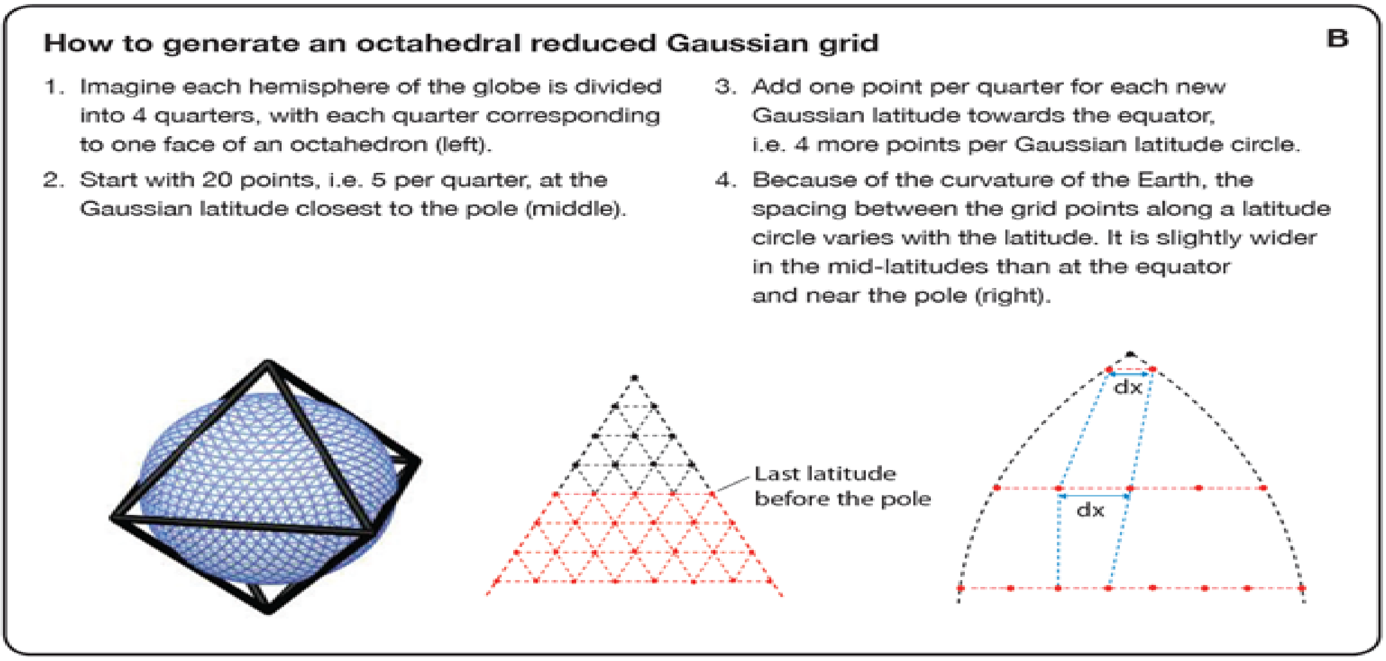


Figure 1. Generation of Octahedral Grid (Ref: Wedi, 2014; ECMWF News Letter, 2015, Number 146)

The TCo grid actually shows much uniform mesh as compared to another realization in the finite volume as shown in Figure 2.

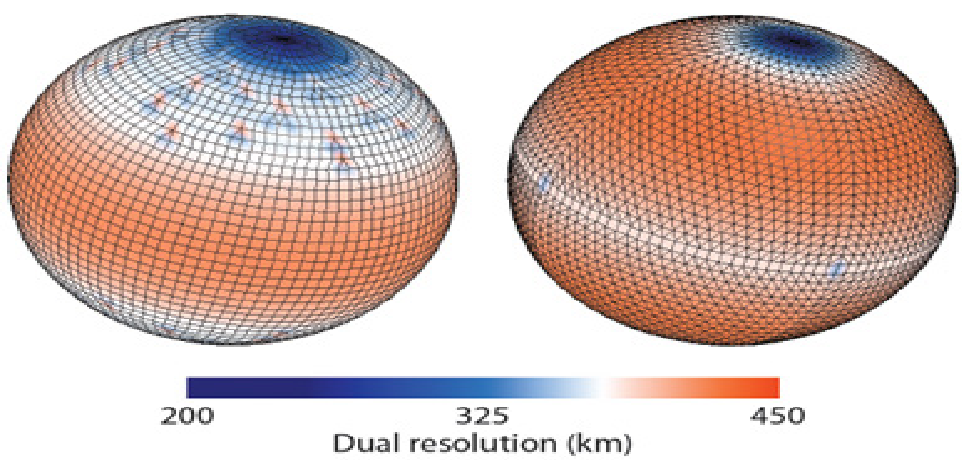


Figure 2: Primary mesh and effective grid spacing in finite volume framework (Smolarkiewicz et al. (2015), (left)) and cubic octahedral (right).

Figure 2 (adopted from ECMWF News Letter 146) demonstrates that the octahedral mesh (right) has a locally more uniform dual-mesh resolution than the mesh (left). Numerical simulation of an idealized baroclinic instability, conducted using IFS model on both the meshes showed the octahedral grid results in higher accuracy and substantially reduced unphysical flow distortions mainly as the approach depends on the underlying mesh which defines the shape of the elementary volumes around which the computations are made (ECMWF New Letter, No. 146, 2015).

Keeping in view above mentioned state-of-the-art technique, it is planned to develop the GFS model in cubic octahedral grid (TCo).

This development is being initiated indigenously and the first version of GFS @TCo765 (which is equivalent to TL1534) has been developed and a forecast for the whole June-July-August-September of 2019 has been completed. TCo grid due to more number of cubes in the tropical region increases the resolution of the model over the tropics than that in the extratropics without any additional resources.

In order to be consistent with the horizontal resolution, vertical levels will be increased.

ICOSAHEDRAL DYNAMICAL CORE

Under the Monsoon Mission Phase II, an innovative proposal has been approved to build the future GFS/CFS in Icosahedral grid framework.

Many major modeling centers across the globe are presently using Icosahedral grid as the framework of NWP model such as NICAM of JAPAN, ICON of DWD etc.

To develop a high resolution numerical model suitable to run on an exascale super computer to simulate Earth system science problems.

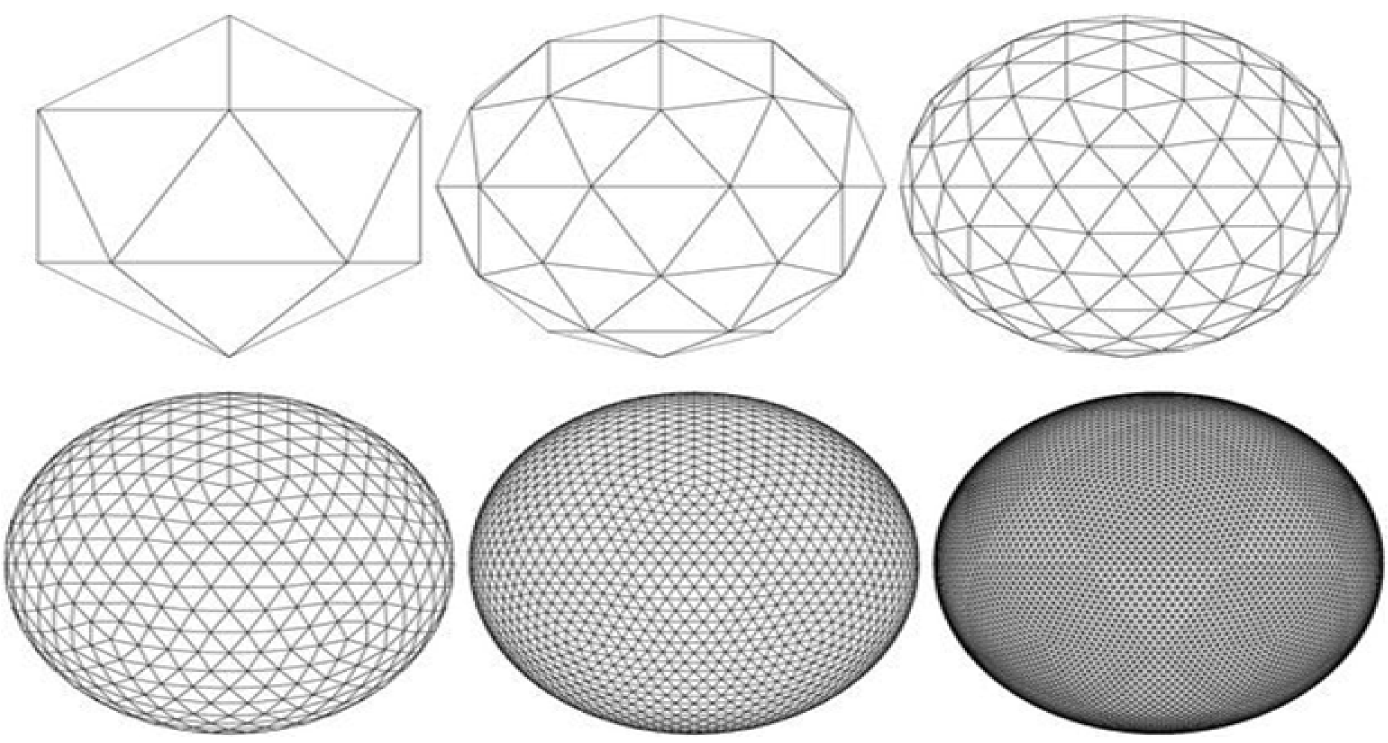


Fig. 3: Icosahedral grids. Icosahedral grids for grid division levels of 0, 1, and 2 (top, from left to right), and 3, 4, and 5 (bottom, from left to right). (Satoh etal. 2014)

The proposal will focus on understanding the basics of model development based on Icosahedral grid and investigation of numerical methods on this grid. It is proposed to develop an improved Dynamical Core (DC) in order to accelerate the execution of weather/ climate forecast models on an advanced super computer. In the long term, it is hoped to replace current traditional numerical weather forecast model with this improved model. More recently, the GFDL finite-volume dynamical core has been modified to use a cubed sphere grid (Putman and Lin, 2007), and has been demonstrated to also be very effective at high resolutions.

In India the efforts to work on dynamical cores is completely lacking. As a result it is proposed that some expertise will be created in developing dynamical cores and associated numerical methods.

Time Lines (Very Flexibl and Long term Goal) and Deliverables

It is expected that by the end of 2024 IITM would have developed some expertise to work on non-hydrostatic models with various complex grids and to run very high resolution models on highly parallel computers.

Model Vertical Resolution

Along with the horizontal resolution, we would like to increase the vertical resolution of the GFS/CFS model by increasing the levels from 64 to ~90 so that more levels are available in the stratosphere.

Modelling Clouds: Convective Parametrization and Microphysics

Present Status: Presently, the GFS/CFS and GEFS systems have a Revised Simplified Arakawa Schubert (RSAS) convective scheme (a mass flux based scheme) and Zhao-Carr (simple) microphysics scheme which only produces tendency of total cloud condensate. RSAS is based on cloud work function trigger and quasi-equilibrium closure which does not hold good at high resolutions (near grey zone) as in TL1534.

Future Plan on Convection Parameterization:(The convection schemes developed would be attempted in different versions of CFS/GFS for climate, seasonal, extended and short range forecasts depending on need and expense to run the model for specific applications).

At the present resolution of GFS/GEFS i. e., at 12.5 km or higher resolution in future (~6 km), the scale would fall within the grey zone where the quasi-equilibrium approximation would not hold good. As a remedy to this and as suggested by Arakawa (2004), Arakawa and Wu, (2012) and Wu and Arakawa (2013), all the physics needs to have scale-aware framework and unified approach. As the cloud and convection is one of the most important process modulating precipitation, heating, wind circulation etc., the existing trigger and convective mass flux estimate will be improved by constraining the model with Indian observations. Additionally, scale-aware convection parameterization schemes will be utilized for higher resolution model in particular.

To reduce the deterministic approach in GFS, the GFS version with stochastic multicloud-multiscale physics and unified turbulence-cloud-convection-radiation with a higher order closure scheme will be developed.

As a future development strategy, the stochastic multi-cloud parameterization will be constrained with Indian observations and also, machine learning approach of convective parameterization will be applied in CFS/GFS to reduce the uncertainties from parameterization. In place of Stochastic total tendency perturbation (STTP), Stochastically Perturbed Parameterization Tendencies (SPPT) will be used in assimilation. Stochastic parameterization will be used in unified manner in physics parameterization.

Cloud Microphysics Parameterization Development

Presently, CFS/GFS has a simple cloud microphysics which generates the tendency of total condensate and does not represent all the cloud processes realistically. Hence, there is a need to improve the cloud microphysics parameterization.

Cloud Microphysics-1

Present status: As the high resolution model needs to have a better representation of grid scale cloud processes or the cloud microphysics for improved stratiform rainfall distribution, an attempt has been made to add a more physically based cloud microphysics scheme incorporating six classes of hydrometeors (WSM6) and utilizing the CAIPEEX data to further improve the scheme.

Major development has been made in CFS in changing the cloud water to rain water conversion parameter based on the critical threshold radius of cloud droplet based on CAIPEEX.

The modified CFS (CFSCR) is found to have an improved mean state, better annual cycle, improved fraction of convective and stratiform rain and convectively coupled tropical waves (Abhik et al. 2017). The improved model CFSCR with resolution of T126 is also found to show an improved skill of precipitation forecast and much improved variability (variance) of monsoon rain as good as the CFSv2 T382 (Rao et al. 2020).

This shows the importance of improving physics being constrained by Indian data in improving the model skill. The modified scheme of WSM6 has also been added now in GFS and the model shows improved forecast of extremes in short range as well.

This approach thus, shows the fidelity of the newly developed scheme in application for seasonal as well as short range high resolution forecast system

Future development: In addition to WSM6, a PDF based unified turbulent-convection-cloud micro-physics parameterization (Cloud Layers Unified By Binormals) would be developed for improving the high resolution model forecast of GFS.

Cloud Microphysics -2

The observations indicate that the ratio of convective and stratiform rain is strongly linked to organization of the MISO (Hazra et al., 2015, 2017a,b; Kumar et al., 2017). By using some recent observations from Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX), the existing cloud microphysics scheme in the CFSv2 is being modified to improve the inadequacy of the model in simulating the mixed phase hydrometeors. Various microphysical processes (such as conversion of cloud water to rain water, cloud water to ice and snow, snow to rain water, etc.) and modification of partitioning of cloud water and ice in the convective scheme have been carried out (Hazra et al., 2017b). The physically based modified convective microphysics (MCM) scheme is implemented in the standard NCEP CFSv2 model (MPHY). The amplitude and spacetime spectra of MISO are improved in association with improved high cloud fraction and convective to stratiform ratio in the MPHY version of the CFSv2. This resulted in much improved simulations of the ISM rainfall, monsoon onset, the annual cycle and skill (Pokhrel et al., 2018). It is also revealed that skill of ISMR in the new version of CFSv2 improved from 0.56 (in control) to 0.71 (Saha et al., 2018).

Proposed Changes and their expected benefits: Efforts are on to further improve the invigoration of lows, depressions, etc. (i.e., synoptic events) through cloud, convection and land-surface feedback. For this purpose, convective microphysics (*e.g.*, conversion of cloud water to rainwater, partitioning cloud water/cloud ice and entrainment mixing processes in cumulus parameterization) and stratiform macrophysics and microphysics (*e.g.*, all microphysical conversion rates/ tendency equations) will be targeted. This targeted development may be helpful to improve synoptic, higher MISO and lower MISO scale of Indian summer monsoon, which will finally impact on the skill of ISMR prediction. Such improvement in synoptic scale activity would be beneficial for improving the stimulation of extreme events (e.g., heavy rainfall events, thunderstorms, cyclones, etc.). Furthermore, dynamical downscaling (based on CFS and WRF) will be taken care of with better understanding of the interaction among aerosol, dynamics, and cloud microphysics on extreme events (e.g., heavy rainfall events, thunderstorms, cyclones etc., Hazra et al., 2013, 2017c). The research on the role of aerosol indirect effect in the process of invigoration of precipitation with a seamless coupled climate model for the monsoon and extreme events is crucial. Improved understanding of the role of cloud-land-atmosphere interactions and better microphysical process rates for ISMR.

Methodology to achieve the proposed changes: Basic research is on to understand cloud processes with the available observed and reanalysis data. To validate the hypothesis on basic understanding, several model sensitivity experiments (both freerun and hindcast) will be carried out. Modification/ development will be carried out on the convective microphysics (*e.g.*, conversion of cloud water to rainwater, partitioning cloud water/cloud ice and entrainment mixing processes in cumulus parameterization) and stratiform macrophysics and microphysics (*e.g.*, all microphysical conversion rates/ tendency equations). Observation from field/ *in-situ* experiments will provide important data for cloud microphysics and aerosols which will help in the study of convective-microphysical processes in coupled climate model. Therefore, guidance from the observations and lessons taken from cloud-resolving modelling over larger and smaller domains will help us for sensitivity experiments in coupled climate model. The interaction between diabatic heating and large-scale dynamics and the vertical structure are important and need to be investigated for the ISO and MJO. Therefore, we wish to progress model's quantitative precipitation (stratiform and convective) and temperature by improving convective microphysical processes although these processes are associated with complex precipitation formations. The physically based developed cloud parameterization scheme can be further tuned by the 'critical' variables based on observation/laboratory experiments in various resolutions of coupled climate models for the seamless prediction system.

Modelling Boundary Layer and Radiation

Current Status: Currently eddy-diffusivity counter gradient (EDCG) planetary boundary layer (PBL) and Rapid Radiative Transfer Model for GCMs (RRTMG) have been used in operational GFS.

Future Development: In tune with the latest cloud and convective schemes, we will be utilizing the scale-aware PBL and Radiation scheme in the high resolution GFS.

Modelling Land Surface and Snow

Present status: A significant part of the ISMR variability is linked with the complex nonlinear feedback between land and atmosphere, and some of these feedbacks are yet not completely understood/ incorporated in the state-of-the-art CGCMs/AGCMs. The slowly varying land surface conditions (soil moisture, vegetation, snow etc.), which are sources of seasonal predictability of ISMR, act as the lower boundary forcing for the atmosphere. Many previous studies have pointed out that the regional feedback between land surface and atmosphere through the variability of soil moisture affect the ISMR variability (*e.g.*, Ferranti *et al.*, 1999; Douville *et al.*, 2002; Koster *et al.*, 2004; Saha *et al.*, 2011, 2012). Also, the remote land surface conditions, *i.e.* the heat-low regions (Iran, Afghanistan, north-west Pakistan) play important role on the performance of the ISMR (Ramage, 1966; Parthasarathy *et al.*, 1992; Rodwell and Hoskins, 1966; Sikka, 1997; Bollasina and Ming, 2013; Rai *et al.*, 2015). Furthermore, the Eurasian snow cover has been recognized as one of the important sources of predictability of the ISMR, which causes memory in the soil through moisture from melting of snow during spring (Hahn and Shukla 1976; Vernekar *et al.* 1995; Sankar-Rao *et al.* 1996; Kripalani and Kulkarni 1999; Bamzai and Shukla 1999; Liu and Yanai 2002; Fasullo 2004; Saha *et al.* 2013, 2016; Ghosh et al. 2019 TAAC). Historical land-use land-cover changes have resulted into changes in the mean monsoon rainfall (Takata, 2009; Krishnan *et al*., 2015; Halder *et al.*, 2015), surface temperatures and moderate rainfall events (Halder *et al.*, 2015).

A multilayer complex snow scheme, implemented in CFSv2 (Saha *et al.*, 2017) shows promising results in simulating ISMR and its global teleconnections (Saha *et al.*, 2018; Sujith *et al.*, 2018). Rai and Saha (2017) highlighted the need for improvements in the parameterization of snow/sea-ice albedo scheme for a realistic simulation of surface temperature. Four different albedo schemes are implemented and evaluated in CFSv2/Noah (Rai *et al*., 2018). Another important area, which affects monsoon rainfall is vegetation and its evolution throughout the season. However, vegetation dynamics is poorly represented in the model. Effects of irrigation on the local climatic conditions including pre-monsoon rainfall and its effects on the rainfall during onset phase of the monsoon are not clearly understood. A large part of the ISMR is due to weather conditions on synoptic and intraseasonal time scale, which have very complex interactions with vegetation and soil moisture that are not understood clearly (*e.g.*, Ferranti *et al.*, 1999; Douville *et al.*, 2002; Koster *et al.*, 2004; Saha *et al.*, 2011, 2012). It is also important to understand the role of land surface processes on the boundary layer convection and rainfall.

Proposed Changes and their expected benefits:

1. Improvements in vegetation scheme of Noah/ CFSv2 may improve the local feedback, which in turn may improve mean and variability of the ISMR.
2. At present, model does not consider effect of irriga-

tion on the local convection and rainfall. However, irrigated land over India is quite large and may potentially affect the ISMR mean, variability and predictability. Irrigation scheme will be implemented and tested in Noah/CFSv2.

3. As land surface processes are intimately linked with boundary layer convection, improvements in the boundary layer scheme over land region will be needed.

Methodology to achieve the proposed changes:

Basic research on understanding the processes on each of the above points will be carried out. The best available observed and reanalysis data will be used to understand the processes. To validate the hypothesis on basic understanding, several model sensitivity experiments will be carried out.

The basic research and model development will be carried out side-by-side and each topic is expected to take about one and half to two years.

I) Vegetation scheme, irrigation 2019-2021;

II) boundary layer scheme and convection 2022-2023.

Multi-Physics Ensemble Prediction System

A seamless multi-model multi-physics ensemble forecast strategy for extended range prediction is proposed based on the newly developed coupled and its atmospheric component models which will be run in seamless nature *i.e.* for the first 15 days are at T574 (23 KM) and the next 17 days are with T382 resolution. This seamless prediction system will fill the gap between weather and climate forecasting in addressing the sub-seasonal to seasonal (S2S) time scale. Further for creating ensembles along-with perturbed initial conditions different physics combination of convective and micro-physics options are sorted out. It is expected that this new strategy of seamless prediction with the newly developed model will improve the skill for extended range prediction in 3rd and 4th week.

Downscaling and AI/ML techniques to improve the spatial representation of predictions

There has been a constant demand for location specific and high resolution area averaged information from weather and climate forecasts. In order to address these issues, we wish to develop tools either based on dynamical downscaling or AI/ML methods to improve the spatial representations of weather and climate forecasts. Recently, it has been shown that dynamical downscaling using coupled regional WRF model has improved spatial representation of seasonal forecasts and its statistics.

On the other hand, statistical downscaling has shown considerable improvement in representation of extended range forecasts at finer spatial scales. It is proposed to utilize these well-established methods to downscale the seasonal and extended range forecasts to finer spatial scales and provide better forecasts. In addition to these traditional methods, fast evolving AI/ML methods will also be explored to improve the spatial representation of the forecasts.

> The seamless prediction with the use of AI/ML would make a paradigm shift from the existing approaches.

Developing a coupled version of GFST1534

As the genesis of weather systems is inherently linked with the Ocean state, it is planned to develop a coupled version of GFSV14 TL1534 by coupling MOM5/MOM6 version of the ocean model to particularly help in tropical cyclone forecast. An initial attempt has been made in forecasting tropical cyclones with CFST574 and comparing it with CFT382 and CFT126.

The experiment has showed improvement of TC

> Coupled version of GFS T1534 would be one of the most important development as ocean coupling at high resolution would significantly help in enhancing the skill of prediction of cyclonegenesis and also the intensity which are the major bottle necks in the current models for cyclone

precipitation and intensity in the higher resolution coupled version of the model.

Development of a machine learning module (in FORTRAN) to be used with ESMF

This module can be used in any parameterization where we can learn from observations on real time. Examples are data assimilation, assumed closure assumptions in parameterization, any other fixed relationships which can be made dynamic,etc.

This is described in the schematic diagram:

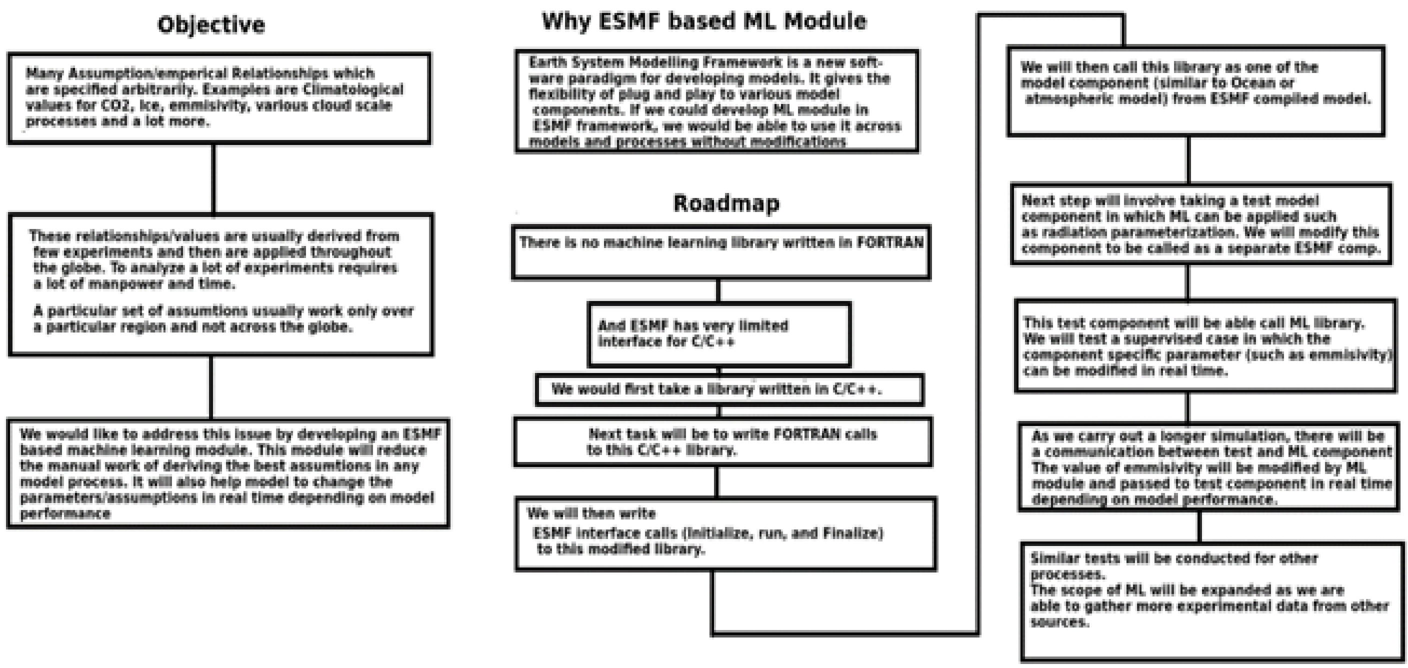


Fig 4. Schematic of implementation of online ML module in GFS/CFS EMS F.

DATA ASSIMILATION

Weakly/strongly coupled LETKF ocean atmospheric coupled Data Assimilation System for CFSv2

A weakly coupled LETKF ocean atmospheric coupled Data Assimilation System for CFSv2 have been developed and implemented at IITM. OSSE (Observation System Simulation Experiments) at T62 resolution for weakly coupled CFS-LETKF has shown significant influence of observations in improving the ocean and atmospheric analysis. In the optimized/ benchmarked weakly coupled CFS-LETKF systems all the ensembles run in parallel. The run time for 06 hour integration (model+ assimilation) is decreased from 50 minutes to 6 minutes with optimization. Using weakly coupled data assimilation (WCDA) system - CFS-LETKF, we prepared the ocean and atmospheric analysis for the years 2000 and 2009 at T126 (40 ensembles) with a possibility to generate real time ocean-atmospheric initial conditions for operational monsoon prediction at various time leads. Preparation of analysis for subsequent years is under progress.The CFS LETKF WCDA system was installed on HPC Pratyush.

CFSv2 seasonal hindcast runs using the new WCDA ocean and atmospheric initial conditions are prepared for the years 2000 to 2007, and is under progress for subsequent years.

Strongly coupled LETKF ocean atmospheric coupled data assimilation system for CFSv2 has been implemented on HPC AADITYA. Sensitivity runs are under progress for tuning the localization, covariance inflation, etc. with an inclination to prepare the best ocean-atmospheric initial conditions for monsoon prediction.

Near future targets (within 3 years) and strategy

1. Benchmarking and preparing analysis from weakly coupled CFS LETKF ocean-atmospheric coupled data assimilation system with 40 ensembles, starting from year 2000.

2. Preparing analysis from weakly coupled CFS LETKF with 40 ensembles, starting from year 2000 at T126 resolution.

3. Benchmarking strongly coupled CFS LETKF ocean atmospheric data assimilation system, with 40 ensembles.

4. Analysing results from (2) and continuing (3).

5. a. Tuning the strongly coupled LETKF data assimilation such as fixing vertical localization length, covariance inflation etc.

b. Comparing and contrasting the analysis error statistics between weakly coupled LETKF analysis and other uncoupled ocean and atmospheric reanalysis.

6. Based on the analysis (i.e. results from 4), providing weakly coupled CFS LETKF ocean – atmospheric initial conditions (2000 to 2017) for hind cast experiments with CFS.

7. Preparing analysis from strongly coupled CFS LETKF with 40 ensembles, starting from year 2000.

8. Developing an ensemble singular vector (as in Yang and Kalnay, 2014) additive inflation method for enhancing ensemble spread, and continuing (7).

9. a. Comparing and contrasting the CFS forecast error characteristics (results from 6) which used ICs from weakly coupled DA, with hindcast runs from uncoupled ICs .

b. Adapting (8) as an additive covariance inflation for both strongly and weakly coupled CFS LETKF; and analysing the results from (7).

10. Based on the analysis (i.e. results from 7), providing strongly coupled CFS LETKF ocean – atmospheric initial conditions (2000 to 2018) for hind cast experiments with CFS.

11. Testing the method developed in (8) as additive inflation for both weakly and strongly coupled CFS LETKF systems for limited number of years.

12. Comparing and contrasting the analysis error statistics between weakly and strongly coupled LETKF systems (results from 6 and 10).

13. Attempting to make analysis (repeating 7 and 10) at higher resolution, T382 or more with both strongly and weakly coupled CFS LETKF systems.

14. Comparing and contrasting the CFS forecast error statistics (results from 6 and 10) which used ICs from weakly and strongly coupled data assimilation at T126 + continuing (13).

15. Based on the results from (14), taking necessary steps/adaptations to make the weakly/strongly coupled CFS LETKF systems for operational usage.

16. Based on the results from 11, preparing the analysis from both strongly and weakly coupled data CFS LETKF data assimilation system at higher resolution (T382 or more) starting from year 2000.

Targets (tentative 3-8 year period) and strategy

1. Adapt and implement the state of the art time to time evolving coupled assimilation techniques such as hybrid filters for monsoon prediction at various time leads.

During recent time, the coupled assimilation with advanced data assimilation techniques has undergone a revolutionary improvement. Hybrid data assimilation techniques are evolving with better prediction skills and lower computational costs. However, it is highly essential to adapt and implement the evolving techniques from time to time. In addition to implementing new techniques, a vigorous analysis is needed to be carried out to check the compatibility of new techniques for operational monsoon prediction at different time leads.

2. Satellite data assimilation such as radiances, precipitation, SSHA etc.; identify and adapt the system for assimilating new state variables.

There has been an unprecedented improvement in availability of ocean and atmospheric data from satellites. Unlike conventional atmospheric data, the majority of ocean data derived from satellites are limited to air-sea boundaries. Strategies are needed to build assimilation of satellite data like radiances, precipitation, SSHA etc. The LETKF system is compatible for incorporating the assimilation of new satellite derived variables to the model state variables by modelling the observation operator. However, it is essential to examine and tune the sensitivity of the model and assimilation system to the new data type by checking its influence on dynamics and other state variables.

3. Decrease the computational costs for operational system by implementing the state of the art techniques like climatological augmentation, running in place, etc.

It has been a well-established fact that increasing the number of ensembles will decrease the forecast error covariance by incorporating the principal modes of error growth at higher degrees of freedom.

However, the availability of computational resources limit the number of ensembles. A limitation of ensemble methods is that the rank of their flow-dependent background-error covariance estimate, and hence the space of possible analysis increments, is limited by the number of forecast ensemble members. A secondary approach is that the rank of background-error covariance can be boosted by augmenting the ensemble members. The additional ensemble members added to the forecast ensemble at analysis time are created by adding a collection of 'climatological' perturbations to the forecast ensemble mean (Kretschmer *et al.*, 2015). These perturbations are constant in time and provide state space directions, possibly missed by the dynamically forecasted background ensemble, in which the analysis increment can correct the forecast mean based on observations. As the climatological perturbations are calculated once, there is negligible computational cost in obtaining the additional ensemble members at each analysis cycle.

Another scheme is proposed to accelerate the spin-up of EnKF by applying a no-cost Ensemble Kalman Smoother, and using the observations more than once in each assimilation window during spin-up in order to maximize the initial extraction of information (Kalnay *et al.*, 2010). It is shown that with the new "running in place" (RIP) scheme, the LETKF spins-up and converges to the optimal level of error faster than 3D-Var or 4D-Var even in the absence of any prior information.

4. Identify the role of Indian - ocean and atmospheric observational networks in improving the monsoon

prediction by using EFSO and Proactive Quality Control techniques, to create the best reanalysis and forecasts product for Indian mainland ocean region. Recently, the Indian ocean (as well the Indian main land) regions have evidenced a major stride in ocean and atmospheric observational networks. The wealth of these observations will have a proactive importance when successfully utilized for operational forecasts as well as research. In addition, the relative role of different observational networks is needed to be quantized to build the best operational forecast system and research products from coupled models. Hence, it is essential to build a systematic strategy to quantize the relative role of different observational networks. Furthermore, this strategy will lay a bencmark in planning the future observational networks.

The state of the art techniques like EFSO (Ensemble Forecast Sensitivity to Observations - Kalnay *et al.*, 2012) and proactive quality control (Ota *et al.*, 2013, Hotta, 2014) will be utilized to quantize the relative role of different observational networks with an ultimate goal to improve the seasonal andsub-seasonal monsoon forecast from coupled assimilation. The system will be very useful to create the best reanalysis and forecast products for Indian mainland and Indian ocean region .

Land data assimilation

Present status: The GDAS system operational at NCMRWF does not have a land data assimilation capability.

Proposed Changes and their expected benefits: The Global Land Data Assimilation System (GLDAS) obtained from GSFC-NASA in collaboration with NCEP will be setup to assimilate snow and soil observations in order to improve the model initialization. GLDAS is based on LETKF assimilation techniques and has the capability to assimilate soil moisture and snow cover/depth. The changes will influence the forecasts across scales (from short range to seasonal).

Methodology to achieve the proposed changes: Different sources of satellite observations/assimilation systems are being explored to be fed to GLDAS for assimilation.

> The coupled data assimilation and land data assimilation will be a breakthrough development and a major component in the seamless prediction system of IITM.

OCEAN MODEL DEVELOPMENTS

Towards Improving Air-Sea interactive Fluxes in Seasonal Prediction Framework

Present Status:

Studies by Wu, Kirtman and Pegion (2007); Pokhrel *et al.* (2012) have shown that the Climate Forecast System (CFS) model simulations have large biases in Latent Heat Flux (LHF; hence net heat flux) in the equatorial Indian Ocean-western Pacific, eastern equatorial Pacific, eastern tropical North Pacific, equatorial Atlantic, north of equatorial Atlantic, and in the western boundary current regions of Kuroshio and Gulf Stream. The difference of mean LHF in these regions exceeds 30 Wm-2. In trade wind belts, the CFS produces smaller LHF, especially in the South Pacific where the difference reaches about 20-30 Wm-2. Wu, Kirtman and Pegion 2007 suggest that the components of Qnet have large components of high frequency variations driven by atmospheric internal dynamics which drives the ocean dynamics in the coupled model. The errors in surface fluxes computation result in wrong feedback between atmosphere and ocean over the tropical Indian Ocean. Wrong SST-flux feedback contributes to the development of unrealistic SST anomalies which might be responsible for model's failure towards the different ocean-atmosphere coupled processes. Recent study by Pradhan *et al.* 2016 has observed that most of the state-of-the-art coupled models have failed to simulate air-sea coupling properly, particularly over tropical Indian ocean. The enhanced air-sea coupling in recent decade leads to frequent occurrences of Indian Ocean Dipoles (IODs) over the Indian ocean. Similar to IOD, other coupled phenomena like El-Nino Southern Oscillation (ENSO) and Madden-Julian Oscillation (MJO) over different ocean basins evolve as a result of air-sea interaction. Air-sea interaction involves exchange of momentum and heat fluxes across the ocean-atmosphere boundary layer. One of the reason for models' failure as mentioned in the study is the erroneous relation between the net heat flux from the ocean and the sea surface temperature (SST) over the Indian ocean. For improving ocean-atmosphere coupling, the air-sea exchange of momentum and heat fluxes has to be accurate enough, at least at diurnal scale. Therefore, more focus will be towards improving air-sea interactions in Monsoon Mission model used for operational monsoon forecasts by improving accuracy in turbulent flux estimation and accounting the factors modulating the air-sea boundary layer fluxes. Two methodologies (latest bulk algorithm and wind-wave interactions) are proposed and discussed in the following sections towards achieving this goal.

Incorporating latest bulk algorithm

The latent heat, sensible heat directly depends on the sea surface temperature and also modulates the sea surface temperature through feedbacks. Incorrect value of SST also leads to inaccurate longwave radiations. The surface stress depends on the stability of the surface layer, which is significantly controlled by the interfacial temperature. So the accuracy of the flux algorithm and hence the ocean-atmosphere coupling greatly depends on the true value of the sea surface temperature. Prior studies have quantified the errors in heat fluxes to be of the order of 100 Wm-2 introduced by the inaccuracy of SST. Fairall *et al.* 1996 have reported that to limit the uncertainty in fluxes within 10 Wm-2, the accuracy required in SST is 0.2 K. However, the measurement made by most of the temperature sensors does not represent the true interfacial temperature or the ocean skin temperature as they are placed at some depth below the surface ocean. Also, the coupled models predict temperatures at some depth beneath the surface, because of the limitation in vertical resolution. Therefore, the measured or simulated temperatures have to be corrected by incorporating the surface processes to estimate the true value of the skin temperatures. Fairall et al., 1996 have addressed the problem by adding two corrections known as cool skin and warm layer corrections in COARE algorithm. The surface of the ocean experiences cooling due to combined effect of sensible heat, latent heat and outgoing long wave radiation. The cooling is confined to upper few mm of the ocean. The cool skin is almost always present and is of the order of 0.1-0.5 K. The solar radiation incident on the ocean surface is mostly absorbed within the upper few meter. The diurnal variation in the upper ocean is significant in magnitude. The upper ocean becomes stably stratified due to solar heating exceeding the cooling due to long wave radiation and turbulent heat transfers. Also, the stratification may suppress the shear driven mixing. The stable layer now is detached from the turbulent layer beneath it and accumulates heat and momentum flux over it. The layer to which the heat and momentum are limited is known as diurnal warm layer (warmer than the layer below). The temperature in the layer can be of the order of 3K. The old bulk algorithm in CFS doesn't account for the corrections for skin temperature and hence doesn't properly account air-sea interactive fluxes. The COARE algorithm is one of the widely used bulk methods for the computation of momentum and heat fluxes from the near surface meteorological measurements, since its inception in 1996. Further improvements introduced for enhancing the accuracy and efficiency of estimation of fluxes.

The latest version of the bulk model (COARE 3.0; Fairall *et al.*, 2003) has a very good accuracy of 5% in weak or moderate wind conditions and 10% in strong wind conditions. Even if COARE 3.0 has proved its good skill in the computation of flux, present-day coupled models (including CFS) are still continuing with old bulk algorithms and hence poor coupling between ocean and atmosphere. The COARE algorithm was developed with the aim to limit the uncertainty in surface fluxes within 10%. The improvements made could take into account the large temperature gradient at the surface and low wind conditions.

Incorporating Impacts of Wind-Wave-Current Interactions

The ocean surface dynamics is significantly different from the bulk ocean because of the small scale turbulent motions and frequently mixed surface layer. The stability and structure of ocean are modulated by processes which can either be buoyancy driven or wind-driven circulations. The convective heating or cooling at the surface layer can modulate buoyancy in the upper ocean which then can generate small-scale turbulent mixing. The turbulence dominated by wind can be generated either due to the stress caused by wind shear or through circulations driven by wind-wave-current interactions.

In the weak wind conditions, the instability is dominated by convective forcing and similarity theory holds good for the boundary layer characteristics (Lombardo and Gaegg, 1989). In strong wind conditions, the surface layer is dominated by wind-generated shear and wave motions. The wind stress and wave-current interaction can generate turbulence in the upper ocean. Indeed, the atmospheric and oceanic boundary layers differ from each other significantly in presence of high winds and waves. The wind stress can create vertical shear in ocean current and waves, which then interacts to produce Langmuir circulations. The turbulence dissipation is enhanced in presence of Langmuir circulations and sometimes surface wave breaking and under this enhancement similarity theory doesn't hold good. The interaction among winds, surface waves, and currents alters the exchanges of momentum and heat between the atmosphere and ocean. Surface gravity waves are generated when wind flow causes stress over ocean boundary layer. When these waves dissipate by breaking, they impart momentum and energy into the ocean. The flux across the boundary and drag coefficient are modified in the presence of high wind and waves. In Langmuir circulation, Stokes drift due to Lagrangian mean wave velocity induces a vortex force, which impacts the heat and momentum budget of upper ocean. Waves can create wind eddies which control the atmospheric fluxes in the lower boundary. Therefore, the inclusion of wind-wave-current interactions is important to improve the air-sea coupling in the global coupled model.

The proposed work can be summarized as follows:

1. Implementing COARE 3.0 in CFSv2 for accurate and efficient estimation of surface heat fluxes (6-12 months).

2. Parameterization scheme for wind-wave-current interaction will be chosen based on the earlier studies by Qiao *et al.* (2004) and Breivik *et al.* (2015). Qiao *et al.* (2004) follows improving SST and heat budget by improving parameterization of wave induced turbulent dissipation. Breivik *et al.* (2015) have tried to include the wave effects by including parameterization for roughness length, Stokes-Coriolis interaction and turbulent energy by breaking waves. The inclusion of wave effects is expected to improve surface layer momentum, heat budget and SST biases. The selected parameterization scheme will be implemented in CFS, which is planned to be carried out in 18 months.

3. The status of Near Inertial Wave will be checked in CFS w.r.t. its amplitude and its phase spectrum. Three sensitivity runs are planned to be carried out following Jochum *et al.* (2013),

(1) with parameterization for boundary layer only,

(2) with parameterization below the boundary layer only and

(3) including both (1) and (2).

The sensitivity runs will be accessed w.r.t. improving SST, flux biases through NIW induced mixing, solving double ITCZ problem in coupled model. This exercise is planned to be completed within 12 months.

Modelling of Land Hydrology and River Runoff

Present status: Presently, the CFS uses a climatological mean state discharge values to the ocean, which is of course, not appropriate. A new routing model component has now been added to CFS in order to pass realistic discharge values to the ocean. Another Variable Infiltration Capacity (VIC) based implementation is also being tested.

Proposed Changes and their expected benefits: The realistic representation of these freshwater fluxes to the ocean is expected to improve the oceanic biases, which in turn must lead to a more realistic representation of the coupled ocean-atmosphere interactions in the coupled model. Sensitivity of the seasonal prediction skill to these changes will also be tested.

Methodology to achieve the proposed changes: The development is being done in-house using the hydrology and routing models available from University of Washington.

Verification Strategies on improvements: Verification will be done using the standard seasonal prediction framework against the control run and observations.

CODE OPTIMIZATION, MAINTENANCE AND SCALING

(FOR ALL THE SPACE AND TIME SCALE PREDICTION)

- Code Optimization exercises is a continuous process and on our new HPC system we have installed intel and Cray compilers. A study had been carried out to test the suitability and these 2 compilers and their optimizations to run the codes faster.
- Efforts to improve the scaling of the CFS together with other general models were carried out by HPC team.
- The results of Optimization and scaling are available at http://pratyush.tropmet.res.in/models/models.php
- It is proposed to convert these codes to complete Fortran 90 and incorporate openmp threads wherever possible to achieve better scalability.
- Maintenance of the codes will be done through SVN.

TARGETS

Targets for Next Generation IITM ESM

During the next 5-6 years, it is planned to undertake the following scientific research and model development activities at the CCCR:

Increased Resolution of IITM-ESM: T62 -> T126

Downscaling of IITM-ESM: T126 coupled -> T574 (stand alone AGCM)

Reliable assessments of the impacts of climate change on: Monsoon hydrological cycle, regional weather and climate extremes, sea-level changes in the global and Indian ocean, marine primary productivity and ocean biogeochemical processes, the global and Himalayan cryosphere.

Separating the roles of natural and anthropogenic forcing on the global climate system, atmosphere-ocean coupled phenomena and the monsoons, and providing reliable assessments of the South Asian monsoon precipitation response to climate change.

Aerosol forcing, Climate and Monsoons: IITM-ESMv2 incorporates the direct radiative effects of aerosols, both natural (*e.g.* dust, sea-salt, volcanic emission etc.) and anthropogenic (sulfate, nitrate, organic carbon, black carbon, etc on the climate system. It is planned to investigate the role of aerosol forcing on the global climate and the Asian monsoon.

Land use and land cover changes: The IITM-ESMv2 has capabilities to address the effects of land use and land cover changes (LULC) on the climate system. This is of particular interest to the Asian region which has undergone major changes in forest cover, agricultural land and vegetation types since pre-industrial times. The IITM-ESMv2 provides a great opportunity to investigate the role of LULC on the regional monsoon precipitation pattern.

Response of Atlantic Meridional Overturning Circulation (AMOC) to global warming: Realistic representation of AMOC is an essential ingredient in climate models in order to study long-term climate variability on decadal, centennial and longer time-scales. The IITM-ESMv2 has significant improvements in simulating the AMOC and polar sea-ice distribution and therby provides a great opportunity to quantify the impacts of global warming on the polar ice caps and the strength of the AMOC. These impacts can in turn affect the global climate, including the Asian monsoon, through alterations in the large-scale atmospheric and oceanic circulation patterns. The AMOC sensitivity experiments will require model simulations extending over at least a few thousand years, which is realizable in the next 4-5 years using the latest multi-petaflop high-performance computing (HPC) facility at IITM, Pune.

Paleo-climate modelling: In the coming 5-6 years, we plan to conduct paleo-climatic modeling studies using the IITM-ESM to understand the past variations of the Asian and Indian monsoons during the last 20000 years (from the Last Glacial Maximum through the Holocene). The modeling experiments will focus on the influence of the Sun-Earth orbital variations on the Earth's climate and monsoons and these simulations should provide key insights into the understanding of the future evolution of the Asian monsoon climate in a warming world.

High-resolution climate change projections: In the next 3-5 years, it is planned to generate global high-resolution (grid size ~ 27 km) climate change simulations and future projections using the atmospheric-only component of the IITM-ESMv2. High-resolution climate change projections are crucial for assessment of changes in weather and climate extremes, changes in mean monsoon summer precipitation and extreme precipitation occurrences, which are generally not captured by low-resolution models. The construction of surface boundary conditions (SST and sea-Ice) for the high-resolution atmospheric-only (IITM-ESMv2-HR-Atmos) model would be based on bias-corrected SST and sea-ice fields obtained from the coarse resolution IITM-ESMv2 simulations. High-resolution climate change projections also serve as important inputs to drive other modeling applications *e.g.*, hydrology, glaciers agriculture, forest fire, health, etc. health, etc.

Tropical and monsoon precipitation: Although the IITM-ESMv2 shows some improvements in capturing the mean summer monsoon precipitation over the Indian region as compared to ESMv1, there is a need to further improve the realism of simulating the Intertropical Convergence Zone (ITCZ) and monsoon precipitation distribution over the Indian and Asian monsoon land region and the adjoining Indo-Pacific oceanic areas; as well as the humidity fields and large-scale tropical divergent circulations (Swapna *et al*. 2018). Focused activities will be taken up to address these scientific issues during the next few years.

Next generation IITM-ESM: Finally, we envisage the development of the next generation IITM-ESM, beyond the next 5 years, having a new dynamical core, interactive aerosols, atmospheric chemistry, and carbon cycle. The next generation IITM-ESM is intended to serve as a community model for further model developments, climate change studies and assessments and monsoon prediction across different time-scales.

Targets for Decadal Prediction

Decadal predictions of monsoon will be initiated and hindcasts will be carried out in next 2-3 years.

Targets for Seasonal Prediction

Seasonal prediction with higher skill over homogeneous regions of India.

Targets for Extended Range Prediction

Higher skill of Extended range prediction for 3rd and 4th week.

Targets for short range prediction

Higher skill (~0.7 anomaly correlation) with seven days forecast and higher skill in capturing the extreme precipitation events with longer lead time.

RESOURCES REQUIRED

In order to achieve the targets specified in this document, following resources are anticipated.

Manpower: Manpower presently at IITM is dwindling due to superannuation of several senior scientists. By 2022, at least 10-15% of employees will be superannuated. In addition to this, in some areas the expertise is presently not available in India/IITM. Hence, new recruitment of scientists with required expertise at different levels is highly required to realize the targets proposed in this document.

Computational Resources: As per the estimate of IITM for the next 5 years, the computational requirement is up to 60 PF for carrying out the proposed activities in this document.

Dedicated Financial support: As was envisaged earlier (2010-19) some of the activities could be achieved due to full support of the MOES and similar support is required to realise the deliverables listed in this document from MOES.

Final outcome: A unified modelling framework for delivering seamless predictions of monsoon weather and climate.

REFERENCES

1. Abhik S., Halder M., Mukhopadhyay P., Jiang X., Goswami B.N., 2013: A possible new mechanism for northward propagation of boreal summer intraseasonal oscillations based on TRMM and MERRA reanalysis, Climate Dynamics, 40, 1611–1624.

2. Abhik S., KrishnaR.P.M., MahakurM., GanaiM., Mukhopadhyay P.and DudhiaJ., 2017: Revised cloud processes to improve the mean and intraseasonal variability of Indian summer monsoon in climate forecast system: Part 1., Journal of Advances in Modeling Earth Systems, 9, 1002–1029, doi:10.1002/2016MS000819.

3. Abhilash S., SahaiA.K., BorahN., ChattopadhyayR., JosephS., SharmilaS., De S. and GoswamiB.N., 2014: Does bias correction in the forecasted SST improve the extended range prediction skill of active-break spells of Indian summer monsoon rainfall?, Atmospheric Science Letters, 15, 114–119, doi:10.1002/asl2.477.

4. Abhilash S., Sahai A.K., BorahN., Joseph S., Chattopadhyay R., SharmilaS., Rajeevan M., Mapes B.E. and KumarA., 2015: Better spread-error relationship in a multimodel ensemble prediction system, Bulletin of the American Meteorological Society, 96, 1228-1229. ISSN 0273-0979.

5. Abhilash S., Sahai A.K., Pattnaik S.and DeS., 2013: Predictability during active break phases of Indian summer monsoon in an ensemble prediction system using climate forecast system, Journal of Atmospheric and Solar-Terrestrial Physics, 100–101, 13–23, doi:10.1016/J.JASTP.2013.03.017.

6. Abhilash S., Mandal R., Dey A., Phani R., Joseph S., Chattopadhyay R., De S., Agarwal N.K., Sahai A.K., Devi S.S., Rajeevan M., 2018: Role of enhanced synoptic activity and its interaction with intraseasonal oscillations on the lower extended range prediction skill during 2015 monsoon season, Climate Dynamics, 51, 3435–3446, doi:10.1007/s00382-018-4089-3.

7. Abhilash S., Sahai A.K., Borah N., Chattopadhyay R., Joseph S., Sharmila S., De S., Goswami B.N., Arun Kumar, 2014: Prediction and monitoring of monsoon intraseasonal oscillations over Indian monsoon region in an ensemble prediction system using CFSv2, Climate Dynamics, 42, 2801–2815, doi:10.1007/s00382-013-2045-9.

8. Abhilash S., Sahai A.K., Borah N., Joseph S., Chattopadhyay R., Sharmila S., Rajeevan M.,

Mapes B.E., Kumar A., 2015: Improved Spread-Error Relationship and Probabilistic Prediction from the CFS-Based Grand Ensemble Prediction System, Journal of Applied Meteorology and Climatology, 54, 1569–1578, doi:10.1175/JAMC-D-14-0200.1.

9. Abhilash S., Sahai A.K., Pattnaik S., Goswami B.N., Arun Kumar, 2014: Extended range prediction of active-break spells of Indian summer monsoon rainfall using an ensemble prediction system in NCEP Climate Forecast System, International Journal of Climatology, 34, 98–113, doi:10.1002/joc.3668.

10. Aimé Fournier, Mark A. Taylor and Joseph J. Tribbia, 2004: The Spectral Element Atmosphere Model (SEAM): High-Resolution Parallel Computation and Localized Resolution of Regional Dynamics, Monthly Weather Review, 132, 726-747, doi:10.1175/1520-0493(2004)132<0726:TSEAMS>2.0.CO;2

11. Arakawa A. and Lamb, V.R., 1977: Computational Design of the Basic Dynamical Process of the UCLA General Circulation Model, Methods Computational Physics, 17, 173-265. doi:10.1016/B978-0-12-460817-7.50009-4

12. Arakawa A., 2004: The cumulus parameterization problem: Past, present, and future, Journal of Climate, 17, 2493–2525.

13. Arakawa Akio and Chien-Ming Wu, 2013: A Unified Representation of Deep Moist Convection in Numerical Modeling of the Atmosphere, Part I, Journal Atmospheric Sciences, 70, 1977-1992.

14. Bamzai A.S. and Shukla J., 1999: Relation between Eurasian snow cover, snow depth, and the Indian summer monsoon: an observational study, Journal of Climate, 12, 3117–32

15. Bollasina Massimo and Yi Ming, 2013: The role of land-surface processes in modulating the Indian monsoon annual cycle, Climate Dynamics, 41(9-10), DOI:10.1007/s00382-012-1634-3.

16. Borah N., Sahai A.K., Chattopadhyay R., Joseph S., Abhilash S. and Goswami B.N., 2013: A self-organizing map-based ensemble forecast system for extended range prediction of active/break cycles of Indian summer monsoon, Journal of Geophysical Research Atmosphere, 118, 9022–9034, doi:10.1002/jgrd.50688.

17. Borah N., Sahai A.K., Abhilash S., Chattopadhyay R., Joseph S., Sharmila S. and KumarA.,

2015: An assessment of real-time extended range forecast of 2013 Indian summer monsoon, International Journal of Climatology, 35, 2860–2876, doi:10.1002/joc.4178.

18. BreivikØyvind, MogensenK., BidlotJ.-R., Balmaseda M.A. and JanssenP.A.E.M., 2015: Surface wave effects in the NEMO ocean model: Forced and coupled experiments, Journal of Geophysical Research: Oceans, 120, 2973–2992, doi:10.1002/2014JC010565

19. Chen C. and XiaoF., 2008: Shallow water model on cubed-sphere by multi-moment finite volume method, Journal of Computational Physics, 227, 5019–5044, doi:10.1016/j.jcp.2008.01.033

20. Davies T., CullenM.J.P., MalcolmA.J., MawsonM.H., StaniforthA., White A.A. and WoodN., 2005: A new dynamical core for the Met Office's global and regional modelling of the atmosphere, Quarterly Journal of the Royal Meteorolgical Society, 131, 1759–178, doi: 10.1256/qj.04.101

21. De S., Hazra A. and Chaudhari H.S. 2016: Does the modification in critical relative humidity of NCEP CFSv2 dictate Indian mean summer monsoon forecast?: evaluation through thermodynamical and dynamical aspects, Climate Dynamics, 46, 1197–122.

22. Douglas G. Hahn and Shukla J., 1976: An Apparent Relationship between Eurasian Snow Cover and Indian Monsoon Rainfall, Journal of the Atmospheric Sciences, 33(12):2461-2462

23. Douville H., ChauvinF., PlantonS., RoyerJ.-F., Salas-Mélia D. and TytecaS., 2002: Sensitivity of the hydrological cycle to increasing amounts of greenhouse gases and aerosols, Climate Dynamics, 20, 45–68.

24. Fairall C.W., BradleyE.F., RogersD.P., EdsonJ.B., YoungG.S., 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment, Journal of Geophysical Research, 101, C2, 3747-376.

25. Fasullo J., 2004: A stratified diagnosis of the Indian monsoon–Eurasian snow cover relationship, Journal of Climate, 17, 1110–22

26. Ganai M., Mukhopadhyay P., Krishna R.P.M. and MahakurM., 2015: The impact of revised simplified Arakawa–Schubert convection parameterization scheme in CFSv2 on the simulation of the Indian summer monsoon, Climate Dynamics, 45, 881–902, doi:10.1007/s00382-014-2320-4.

27. Ganai M., Mukhopadhyay P., KrishnaR.P.M., Abhik S.and HalderM., 2019: Revised cloud and convective parameterization in CFSv2 improve the underlying processes for northward propagation of Intraseasonal oscillations as proposed by the observation-based study, Climate Dynamics, 53, 2793-2805, doi:10.1007/s00382-019-04657-9.
28. Ganai M., KrishnaR.P.M., Mukhopadhyay P. and MahakurM., 2016: The impact of revised simplified Arakawa-Schubert scheme on the simulation of mean and diurnal variability associated with active and break phases of Indian summer monsoon using CFSv2., Journal of Geophysical Research Atmosphere, 121, 9301–9323, doi:10.1002/2016JD025393.
29. Ghosh S., Bhatla R., Mall R.K., Srivastava P.K., Sahai A.K., Aspect of ECMWF downscaled Regional Climate Modeling in simulating Indian summer monsoon rainfall and dependencies on lateral boundary conditions, Theoretical and Applied Climatology, 135, February 2019, DOI:10.1007/s00704-018-2432-6, 1559-1581
30. Goswami B.B. and Khouider B., Phani R., Mukhopadhyay P., Majda A.J., 2017: Improved Tropical Modes of Variability in the NCEP Climate Forecast System (Version 2) via a Stochastic Multicloud Model, Journal of Atmospheric Sciences, 74, 3339–3366, doi:10.1175/JAS-D-17-0113.1.
31. Goswami B.B., KhouiderB., PhaniR., Mukhopadhyay P. and MajdaA.J., 2017: Improving synoptic and intraseasonal variability in CFSv2 via stochastic representation of organized convection, Geophysical Research Letters, 44, 1104–1113, doi:10.1002/2016GL071542.
32. Goswami B.B., KhouiderB., PhaniR., Mukhopadhyay P. and MajdaA.J., 2017: Implementation and calibration of a stochastic multicloud convective parameterization in the NCEP Climate Forecast System (CFSv2), Journal of Advances in Modeling Earth Systems, 9, 1721–1739, doi:10.1002/2017MS001014.
33. Goswami B.B., KrishnaR.P.M., Mukhopadhyay P., KhairoutdinovM., Goswami B.N., 2015: Simulation of the Indian Summer Monsoon in the Superparameterized Climate Forecast System Version 2: Preliminary Results, Journal of Climate, 28, 8988–9012, doi:10.1175/JCLI-D-14-00607.1.
34. Govett M., Middlecoff J.and HendersonT., 2010: Running the NIM next-generation weather model on GPUs. 10th IEEE/ACM Int. Conf. on Cluster, Cloud and Grid Computing,

Melbourne, Australia, Institute of Electrical and Electronics Engineers/Association for Computing Machinery, 792–796,doi:10.1109/CCGRID.2010.106.

35. Hazra A., ChaudhariH.S., Saha S.K., Pokhrel S. and Goswami B.N., 2017: Progress Towards Achieving the Challenge of Indian Summer Monsoon Climate Simulation in a Coupled Ocean-Atmosphere Model. Journal of Advances in Modeling Earth Systems, 9, 2268–2290, doi:10.1002/2017MS000966.

36. Hotta Daisuke, 2014: Proactive Quality Control based on Ensemble Forecast Sensitivity to Observations, PhD thesis, doi:10.13016/M23W3P

37. Jochum Markus, 2015: The Impact of Oceanic Near-Inertial Waves on Climate., J. of Climate, 26, 2833-2844, DOI: 10.1175/JCLI-D-12-00181.1

38. Joseph S, Sahai A.K., PhaniR., MandalR., Dey A.and Chattopadhyay R., 2017: Evaluation of Extended Range Forecast Skill on Subdivisional scale over India, IITM Research Report No. RR-137, ESSO/IITM/SERP/SR/01(2017)/188.

39. Joseph S., Mandal R., Sahai A.K., PhaniR., Dey A.and Chattopadhyay R., 2018: Diagnostics and Real - Time Extended Range Prediction of Heat Waves over India, IITM Research Report, RR - 141 ESSO/ IITM/SERP/SR/03(2018)/192.

40. Joseph S., Sahai A.K., Abhilash S., Chattopadhyay R., Borah N., Mapes B.E., Rajeevan M., Kumar A., 2015: Development and Evaluation of an Objective Criterion for the Real-Time Prediction of Indian Summer Monsoon Onset in a Coupled Model Framework, Journal of Climate, 28, 6234–6248, doi:10.1175/JCLI-D-14-00842.1.

41. Joseph S., Sahai A.K., Chattopadhyay R., Sharmila S., Abhilash S., Rajeevan M., Mandal R., Dey A., Borah N., Phani R., 2016: Extremes in June rainfall during the Indian summer monsoons of 2013 and 2014: observational analysis and extended-range prediction, Quarterly Journal of the Royal Meteorological Society, 142, 1276–1289, doi:10.1002/qj.2730.

42. Joseph S., Sahai A.K., Sharmila S., Abhilash S., Borah N., Chattopadhyay R., Pillai P.A., Rajeevan M., Arun, 2015: North Indian heavy rainfall event during June 2013: diagnostics and extended range prediction, Climate Dynamics, 44, 2049–2065, doi:10.1007/s00382-014-2291-5.

43. Kalnay Eugenia, Yoichiro Ota, Takemasa Miyoshi and Junjie Liu, 2012: A simpler formu-

lation of forecast sensitivity to observations: application to ensemble Kalman filters, Tellus A: Dynamic Meteorology and Oceanography, 64:1, 18462, DOI: 10.3402/tellusa.v64i0.18462

44. Koster R.D., Dirmeyer P.A. and GuoZ.C., 2004: Regions of strong coupling between soil moisture and precipitation, Science, 305, 1138–1140.

45. Kripalani R.H. and Kulkarni A.A., 1999: Climatology and variability of historical Soviet snow depth data: Some new perspectives in snow-Indian monsoon teleconnections, Climate Dynamics, 15, 1999, 475-489

46. Krishna R.P.M., Abhik S., Goswami B.B., Ganai M., Mahakur M., Deshpande M., Mukhopadhyay P., Das R.S., Khairoutdinonv M., Dudhia J. and Goswami B.N., 2016: Improvement of cloud and convective Parameterizations in Climate Forecast System Version 2 (CFSv2): Indian Summer Monsoon perspective, IITM Research Report, RR 135, 1-51, ISSN 0252-1075.

47. Krishna R.P.M., Rao S.A., Srivastava A., Kottu H.P., Pradhan M., Pillai P., Dandi R.A. and Sabeerali C.T., 2019: Impact of convective parameterization on the seasonal prediction skill of Indian summer monsoon, Climate Dynamics, 6227-6243, doi:10.1007/s00382-019-04921-y.

48. Krishnan R., Swapna P., Vellore Ramesh, Narayanasetti Sandeep, Prajeesh A.G., Dey Choudhury Ayantika, Singh Manmeet, Sabin T.P., Sanjay J., 2018: The IITM Earth System Model (ESM): Development and Future Roadmap. Chapter 9 in the book: Current trends in the representation of physical processes in weather and climate models. Editors. David Randall, Srinivasan J., Nanjundiah Ravi, Mukhopadhyay P., Springer Publications.

49. Liu X. and Yanai M., 2002: Influence of Eurasian spring snow cover on Asian summer rainfall, International Journal of Climatology, 22, 1075–89

50. Mukhopadhyay P., Prasad V.S., Krishna R.P.M., Deshpande M., Ganai M., Tirkey S., Sarkar S., Goswami T., Johny C.J., Roy K., Mahakur M., Durai V.R., M Rajeevan, 2019: Performance of a very high-resolution global forecast system model (GFS T1534) at 12.5 km over the Indian region during the 2016–2017 monsoon seasons, Journal of Earth System Science, 128, August 2019, DOI:10.1007/s12040-019-1186-6, 1-18

51. Ota Yoichiro, John C. Derber, Eugenia Kalnay and Takemasa Miyoshi, 2013: Ensemble-based observation impact estimates using the NCEP GFS, Tellus A: Dynamic Meteorology and Oceanography, 65:1, 20038, DOI: 10.3402/tellusa.v65i0.20038

52. Pai D.S., Rao S.A., Senroy S., Pradhan M., Pillai P.A. and Rajeevan M., 2017: Performance

of the operational and experimental long-range forecasts for the 2015 southwest monsoon rainfall, Current Science, 112, 68-75.

53. Parthasarathy B., Rupa Kumar K., Kothawale D.R., 1992: Indian summer monsoon indices: 1871-1990, Meteorological Magazine, 121, 1992, 174-186

54. Pokhrel S., Hazra A., Chaudhari H.S., Saha S.K., Paulose F., Krishna S., Krishna R.P.M. and Rao S.A., 2018: Hindcast skill improvement in Climate Forecast System (CFSv2) using modified cloud scheme, International Journal of Climatology, doi:10.1002/joc.5478.

55. Prasad V.S. and JohnyC.J., 2016: Impact of hybrid GSI analysis using ETR ensembles, Journal of Earth System Science, 125, 521–538, doi:10.1007/s12040-016-0673-2.

56. Prasad V.S., Johny C.J. and SodhiJ.S., 2016: Impact of 3D Var GSI-ENKF hybrid data assimilation system, Journal of Earth System Science, 125, 1509–1521, doi:10.1007/s12040-016-0761-3.

57. Putman W. and LinS., 2007: Finite-volume transport on various cubed-sphere grids, Journal of Computational Physics, 227(1), 55–78, doi:10.1016/j.jcp.2007.07.022.

58. Putman W. and LinS., 2009: A finite-volume dynamical core on the cubed-sphere grid, in Numerical Modeling of Space Plasma Flows: Astronum-2008, Astron. Soc. Pac. Conf. Ser., 406, 268–276, Astron. Soc. of the Pac., San Francisco, Calif.

59. Qiao Fangli, Ma, Ji-An, Yang, Yong-Zeng and Yuan Yeli 2004: Simulation of the Temperature and Salinity Along 36 N in the Yellow Sea with a Wave-Current Coupled Model. Journal of the Korean Society of Oceanography. 39, 35-45.

60. Rajeevan M., Bhate J., Kale J.D. and Lal B., 2006: High resolution daily gridded rainfall data for the Indian region: Analysis of break and active, Current Science., 91., 296-306.

61. Ramage C.S., 1966: The summer atmospheric circulation over the Arabian Sea., Journal of Atmospheric Sciences, 23, 144-150.

62. Ramu D.A., RaoSuryachadra A., Pillai P., Pradhan M., George G., RaoNagarguna D., Mahapatra S., Pai D.S., Rajeevan M., 2017: Prediction of seasonal summer monsoon rainfall over homogenous regions of India using dynamical prediction system, Journal of Hydrology, 546, 103–112, doi:10.1016/j.jhydrol.2017.01.010.

63. Rancic´ M., Purser R.J. and MesingerF., 1996: A global shallowwater model using an

expanded spherical cube: Gnomonic versus conformal coordinates, Quarterly Journal of the Royal Meteorological Society, 122, 959–982, doi:10.1002/qj.49712253209.

64. Rao S.A., Goswami B.N., Sahai A.K., Rajagopal E.N., Mukhopadhyay P., Rajeevan M., Nayak S., Rathore L.S., Shenoi S.S.C., Ramesh K.J., Nanjundiah R.S., Ravichandran M., Mitra A.K., Pai D.S., Bhowmik S.K.R., Hazra A., Mahapatra S., Saha S.K., Chaudhari H.S., Joseph S., Pentakota S., Pokhrel S., Pillai P.A., Chattopadhay R., Deshpande M., Krishna R.P.M., SiddharthRenu, Prasad V.S., Abhilash S., Maini Parvinder, 2019: Monsoon Mission : A targeted activity to improve monsoon prediction across scales, Bulletin of the American Meteorological Society, 2509-2532, DOI:10.1175/BAMS-D-17-0330.1

65. Rao S.A., Pillai P.A., Pradhan M., Srivastava A., 2019: Seasonal prediction of Indian summer monsoon in India: The past, the present and the future, Mausam, 70, April 2019, 265-276.

66. Rodwell M. and Hoskins, B., 1966: Monsoons and the dynamics of deserts., Quarterly Journal of the Royal Meteorological Society, 122, 1385-1404

67. Ronchi C., IaconoR., PaolucciP.S., 1996: The "Cubed Sphere": A New Method for the Solution of Partial Differential Equations in Spherical Geometry, Journal of Computational Physics, 124, 93-114, doi:10.1006/jcph.1996.0047

68. Rossmanith J.A., 2006: A wave propagation method for hyperbolic systems on the sphere, Journal of Computational Physics, 213, 629–658, doi:10.1016/j.jcp.2005.08.027.

69. Sadourny Robert, 1972: Conservative Finite-Difference Approximations of the Primitive Equations on Quasi-Uniform Spherical Grids, Monthly Weather Review, 10, 136-144. doi:10.1175/1520-0493(1972)100<0136:CFAOTP>2.3.CO;2

70. Saha S.K., HazraA., Pokhrel S., Chaudhari H.S., SujithK., RaiA., Rahaman H.and GoswamiB.N., 2019: Unraveling the Mystery of Indian Summer Monsoon Prediction: Improved Estimate of Predictability Limit, Journal of Geophysical Research: Atmospheres, 124, 1962-1974, DOI:10.1029/2018JD030082,

71. Saha S.K., SujithK., Pokhrel S., Chaudhari H.S. and HazraA., 2017: Effects of multilayer snow scheme on the simulation of snow: Offline Noah and coupled with NCEPCFSv2, Journal of Advances in Modeling Earth Systems, 9, 271–290, doi:10.1002/2016MS000845.

72. Saha S.K., Pokhrel S. and Chaudhari H.S., 2013: Influence of Eurasian snow on Indian

summer monsoon in NCEP CFSv2 freerun,Climate Dynamics, 41, 1801–1815, doi:10.1007/s00382-012-1617-4.

73. Saha Subodh K., Pokhrel S., Salunke K., Dhakate A., Chaudhari H.S., Rahaman H., Sujith K., Hazra A., Sikka D.R., 2016: Potential predictability of Indian summer monsoon rainfall in NCEP CFSv2, Journal of Advances in Modeling Earth Systems, 8, 1-25, DOI:10.1002/2015MS000542

74. Saha Suranjana, Shrinivas Moorthi, Xingren Wu, Jiande Wang, Sudhir Nadiga, Patrick Tripp, David Behringer, Yu-Tai Hou, Hui-Ya Chuang, Mark Iredell, Michael Ek, Jesse Meng, Rongqian Yang, Malaqui´As Pen˜ A Mendez, Huug Van Den Dool, Qin Zhang, Wanqiu Wang, Mingyue Chen, and Emily Becker, 2014: The NCEP climate forecast system v2, Journal of Climate, 27, 2185–2208, doi:10.1175/JCLI-D-12-00823.1.

75. Sahai A.K., Chattopadhyay R., Joseph S., Krishna R.P.M., D.R. Pattnaik and Abhilash S., 2018: Seamless prediction of monsoon onset and active/break phases, Chapter in the book The Gap Between Weather and Climate Forecasting, edited by Andrew Robertson and Frederic Vitart, www.elsevier.com/books/sub-seasonal-to-seasonalprediction/robertson/978-0-12-811714-9

76. Sahai A.K., Chattopadhyay R., Joseph S., R. Mandal, A. Dey, Abhilash S., Krishna R.P.M. and BorahN., 2015b: Real-time performance of a multi-model ensemble-based extended range forecast system in predicting the 2014 monsoon season based on NCEP-CFSv2, 109.

77. Sahai A.K., Chattopadhyay R., Joseph S., Krishna R.P.M. and Abhilash S., 2016: Extended Range Prediction System and its Application, Vayu Mandal, 42, 75-96.

78. Sahai A.K., Abhilash S., Chattopadhyay R., BorahN., Joseph S., Sharmila S.and Rajeevan M., 2015: High-resolution operational monsoon forecasts: an objective assessment, Climate Dynamics, 44, 3129–3140, doi:10.1007/s00382-014-2210-9.

79. Sahai A.K., Sharmila S., Chattopadhyay R., Abhilash S., Joseph S., Borah N., Goswami B.N., Pai D.S., Srivastava A.K., 2017: Potential predictability of wet/dry spells transitions during extreme monsoon years: optimism for dynamical extended range prediction, Natural Hazards, 88, 853–865, doi:10.1007/s11069-017-2895-2.

80. Sahai A.K., Sharmila S., Abhilash S., Chattopadhyay R., BorahN., Krishna R.P.M., Joseph S., RoxyM., DeS., Pattnaik S.and PillaiP.A., 2013. Simulation and Extended range prediction of Monsoon Intraseasonal Oscillations in NCEP CFS/GFS version 2 frame work, Current Science,

104, 1394-1408. ISSN 0011-3891
81. Sankar-Rao M., Lau Song YangK.M., 1996: On the Relationship Between Eurasian Snow Cover and the Asian Summer Monsoon, International Journal of Climatology, 16, 605-616.
82. Saranya Ganesh S., Sahai A.K., Abhilash S., Joseph S., DeyA., MandalR., Chattopadhyay R. and Krishna R.P.M., 2018: A New Approach to Improve the Track Prediction of Tropical Cyclones Over North Indian Ocean, Geophysical Research Letters, 45, 7781–7789, doi:10.1029/2018GL077650.
83. Sharmila S., Joseph S., Sahai A.K., Abhilash S. and Chattopadhyay R., 2015: Future projection of Indian summer monsoon variability under climate change scenario: An assessment from CMIP5 climate models, Global and Planetary Change, 124, 62–78, doi:10.1016/j.gloplacha.2014.11.004.
84. Sikka D.R., 1997, Desert Climate and Its Dynamics, Current Science, 72, 35-46.
85. Staniforth Andrew, Nigel Wood, 2008: Aspects of the dynamical core of a nonhydrostatic, deep-atmosphere, unified weather and climate-prediction model, Journal of Computational Physics, 227, 3445–3464
86. Swapna P., Krishnan R., Sandeep N., Prajeesh A.G., Ayantika D.C., Manmeet S. and Vellore R. 2018, Long-term climate simulations using the IITM-ESMv2 with focus on the South Asian monsoon, Journal of Advances in Modeling Earth Systems, doi: 10.1029/2017MS001262 00016.1)JAS-D-13-0382.1.
87. Swapna P., Roxy, M.K., Aparna K., Kulkarni K., Prajeesh A.G., Ashok, K., Goswami B.N., 2015: The IITM earth system model: Transformation of a seasonal prediction model to a long-term climate model, Bulletin of the American Meteorological Society, 96(8), 1351–1368. doi:10.1175/BAMS-D-13-00276.1
88. Sylvie Malardel, Nils Wedi, Willem Deconinck, Michail Diamantakis, Christian Kühnlein, George Mozdzynski, Mats Hamrud, Piotr Smolarkiewicz, 2015: A new grid for the IFS, ECMWF Newsletter No. 146 – Winter 2015/16, 23-28.
89. Takata Kumiko, Kazuyuki Saito and Tetsuzo Yasunari, 2009: Changes in the Asian monsoon climate during 1700–1850 induced by preindustrial cultivation, Proceedings of the National Academy of Sciences, 16, 2009 106 (24) 9586-9589; doi:10.1073/pnas.0807346106.

90. Tomita H., Satoh M., 2004: A new dynamical framework of nonhydrostatic global model using the icosahedral grid, Fluid Dynamics Research, 34, 357–400.
91. Ullrich P.A., JablonowskiC. and Van LeerB., 2010: High-order finite-volume methods for the shallow-water equations on the sphere, Journal of Computational Physics, 229, 6104–6134, doi:10.1016/j.jcp.2010.04.044.
92. Vernekar A.D., Zhou J, Shukla J., 1995: The effect of Eurasian snow cover on the Indian monsoon, Journal of Climate, 8: 248–266
93. Walko R.L. and AvissarR., 2008a: The Ocean–Land–Atmosphere Model (OLAM): Shallow-water tests, Monthly Weather Review, 136, 4033–4044.
94. Wedi N.P., 2014: Increasing horizontal resolution in numerical weather prediction and climate simulations: illusion or panacea?, Philosophical Transaction of the Royal Society A, 372:20130289,doi:10.1098/rsta.2013.0289
95. Wedi N.P., Hamrud M, Mozdzynski G., 2013: A fast spherical harmonics transform for global NWP and climate models, Monthly Weather Review, 141, 3450–3461, doi:10.1175/MWRD-13-00016.1)
96. Wu C.-M., and ArakawaA., 2014: A unified representation of deep moist convection in numerical modeling of the atmosphere, Part II, Journal of Atmospheric Sciences, 71, 2089–2103, doi:10.1175/JAS-D-13-0382.1.
97. Wu Renguang, Ben P. Kirtman, Kathy Pegion, 2007: Surface latent heat flux and its relationship with sea surface temperature in the National Centers for Environmental Prediction Climate Forecast System simulations and retrospective forecasts, Geophysical Research Letters, 34, L17712, doi:10.1029/2007GL030751.
98. Yeh K-S, Côté J, Gravel S., Méthot A., Patoine A., Roch M., Staniforth A., 2002: The CMC–MRB global environmental multiscale (GEM) model: Part III – Nonhydrostatic formulation Monthly Weather Review, 130, 339–356.