Monsoon Mission

Major Achievements MM-Phase1

Dynamical Prediction System

Improving Prediction Skill

Human Resource Development

International Collaboration

High Performance Computing

सत्यमेव जयते

Earth System Science Organisation (ESSO)
Ministry of Earth Sciences
Govt. of India

Major Achievements of the Monsoon Mission Phase-1 (July 2012 - July2017): Report

Contributors:

Suryachandra A. Rao, B. N. Goswami, M. Rajeevan, S. Nayak, D. R. Sikka, J. Srinivasan, R. Krishnan, R. S. Nanjundiah, L.S. Rathore, Swati Basu, E.N. Rajagopal, Satish Shenoi, M. Ravichandran, A.K. Sahai, A. K. Mitra, G. Iyenger, S. K. RoyBhowmick, D. S. Pai, P.A. Francis, D. Sengupta, P. Maini, C. Gnanaseelan, P. Mukhopadhyay, A. Hazra, S. Mahapatra, Subodh K. Saha, H. S. Chaudhari, Samir Pokhrel, Phani M. Krishna, P. Sreenivas, Prasanth Pillai, R. S. Mahesh Kumar, Siddharth Kumar, S. Mandke, A.A. Deo, N. K. Agarwal, Susmitha Joseph, S. De, S. Abhilash, Rajib Chottopadhyay, Medha Deshpande, Prem Singh, Anant parekh, Jasti S. Choudhary, Anika Arora, A. Ramu Dandi, Archana Rai, Renu Das, Ankur Srivastava, M. Pradhan, Malay Ganai, S. Tirkey, S. Malviya, S. Sarkar, T. Goswami, R. Kakatkar, Deepa J. S., D. W. Ganer, S. S. Naik, Raju Mandal, Avijit Dey, Ashish Dhakate, Kiran Salunke, V. Vasudevan, C. T. Sabeerali, Gibies G., D. Nagarjuna, H. Gandham

+ All members of SRMC and SSC + All PIs and Co-PIs of National and International Projects of Monsoon Mission+ M.M.D. Personnel (Rakesh, Sandeep, Krunal & Vikash)

The Earth System Sciences Organization (ESSO)
Ministry of Earth Sciences (MoES), Government of India

October, 2017

Contents :

Executive Summary

Indian Summer Monsoon (ISM) Rainfall amounts to more than 80% of the annual rainfall over India and the dependence of agriculture, drinking water and energy production on the rainfall makes summer monsoon the lifeline for a large fraction of the world's population. The economy, life and property in the region are vulnerable to significant variability of the ISM on intra-seasonal, inter-annual and inter-decadal time scales. Although the year-to-year variation of seasonal means all India rainfall (ISMR) is only about 10% of the mean (86 cm), there is strong link between the country's food production and even the gross domestic product (GDP) on it. Hence, predicting ISM rainfall is of great socio-economic importance and has been attempted for many decades, albeit with limited success. In recent times, with the dynamical models, several new approaches (high resolution, super parameterizations, data assimilation etc.) have shown that the variability in tropics can be reasonably resolved, thereby creating optimism for improving the monsoon prediction. The present coupled models developed by international climate centres have better prediction skill of seasonal rainfall over tropical oceans (more than 0.7 out of 1.0), however, the Asian monsoon rainfall (not Indian monsoon alone) prediction skill was below 0.1. Keeping in view the importance of a dynamical prediction framework, the Earth System Science Organization (ESSO) of Ministry of Earth sciences (MoES), after obtaining cabinet approval, has launched the "Monsoon Mission" in 2012 to develop a dynamical prediction framework and to improve monsoon prediction skill.

At the time of launching of Monsoon Mission, in India, there was no coupled Ocean-atmosphere dynamical modelling frame work in place to make either operational or experimental forecasts of seasonal mean and monsoon active/ break conditions. Until recently, modelling activity in India was limited to just run the models and test its skill and make experimental forecasts on standalone AGCMs, mainly due to lack of trained manpower to work on model developments and lack of HPC infrastructure to run these models. Several academic and R&D institutes in India are carrying out research in the above fields on different models (both empirical and dynamical), including diagnostics of why the models fail to predict a particular year's monsoon performance. However, the knowledge gained at these institutes is not translated into improvement of operational weather and climate forecasts, as there is no concerted effort to link the knowledge gained at academic and R&D organizations to improve operational models as all these organization are working at their will on different models which they can obtain easily. Therefore, there is a need of concerted efforts between the academic, R&D institutes and operational organizations for improvement of operational weather and climate forecasts, especially using specific models which can give reasonably accurate forecasts. Monsoon mission was envisaged to bring focus to these research efforts.

Aim and major objectives of monsoon mission

Monsoon mission was focused on the below two major aims.

- To build a working partnership between the Academic and Research& Development Organizations, both national and international and the MoES to improve the monsoon forecast skill over the country.

- To setup a state of the art dynamical modelling frame work for improving prediction skill of (a) Seasonal and Extended range predictions and (b) Short and Medium range (up to two weeks) prediction.

Execution of monsoon mission

Four MoES institutes (ESSO-IITM, ESSO-NCMRWF, ESSO-IMD and ESSO-INCOIS) have partnered actively in this important and ambitious program to realize the above objectives. The ocean-atmosphere coupled dynamical model "Climate Forecast System, Version-2" (CFSv2, adopted from NCEP, USA) was chosen as the base model for extended range (predictions up to 3 weeks in advance) to seasonal (for the SW monsoon season of June to September) prediction of monsoon. ESSO-IITM is responsible for running and experimenting at very high horizontal resolution of 38km and carried out developmental activates in the direction of improving convective parameterization, cloud microphysics, parameterization of land surface processes. ESSO-IITM also worked on improving short range prediction using atmospheric model of CFSv2 (Global climate system, GFS). Infrastructure required for these developmental activities was made available, at IITM and NCMRWF, as part of monsoon mission by procuring and installation of High performance computing (HPC) facility with combined performance of 1.2 Peta Flops. ESSO-NCMRWF worked on improving short to medium range forecasts using Unified Model (UM) of UK Met. Office (UKMO) for short to Medium range weather forecast (prediction up to 10 days in advance). ESSO-NCMRWF is also responsible for implementing and operationalization of the atmospheric data assimilation system for both UM and GFS models. Ocean data assimilation system was set up at ESSO-INCOIS and was involved in providing initial conditions of ocean data for different forecasts using GODAS. For building a working partnership between the Academic and R& D Organizations and the MoES organizations (IITM, IMD, NCMRWF), several national and international projects were funded through Monsoon Mission. A total of about 40 projects (including National and International projects) have been funded by MoES, through Monsoon Mission. Out of these, 20 International projects (from different countries, like USA, UK, Australia, Canada, France, Japan & UAE) have been funded, mainly for modeling aspects. These projects resulted in the following outcomes.

- coupled data assimilation based on LETKF
- model development activities to improve dynamical predictions system
- downscaling the model forecasts at higher resolution
- better understanding of model behavior and suggestions for further improvement

Around 10 Ph.Ds are produced under the program along with more than 200 research publications.

Major achievements of Monsoon Mission

- ✓ **Developed seasonal prediction model with highest skill among global models in the world for predicting monsoon at high resolution of 38km**.

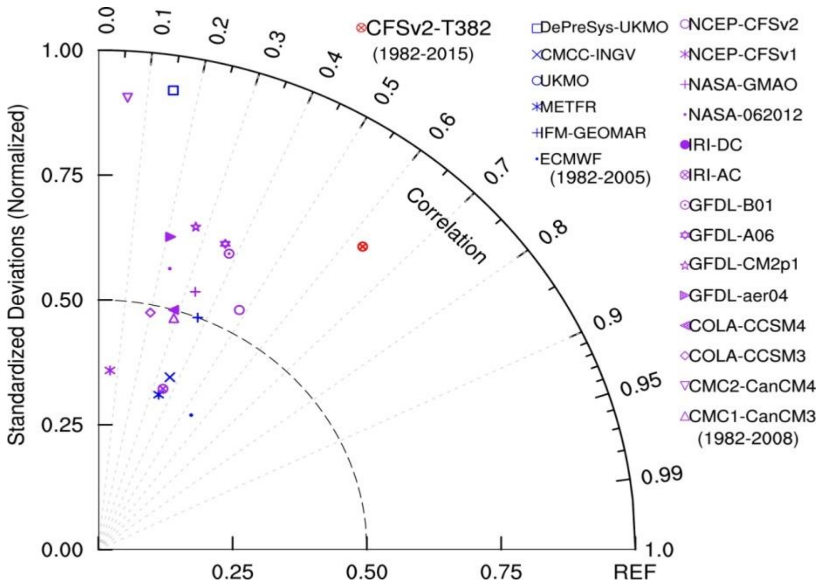


Figure 1: Taylor diagram showing the skill of present generation seasonal prediction models along with monsoon mission CFSv2-T382 (red dot).

- ✓ **Skillful prediction of monsoon active/break cycles at extended range: at par with the best in the world.**

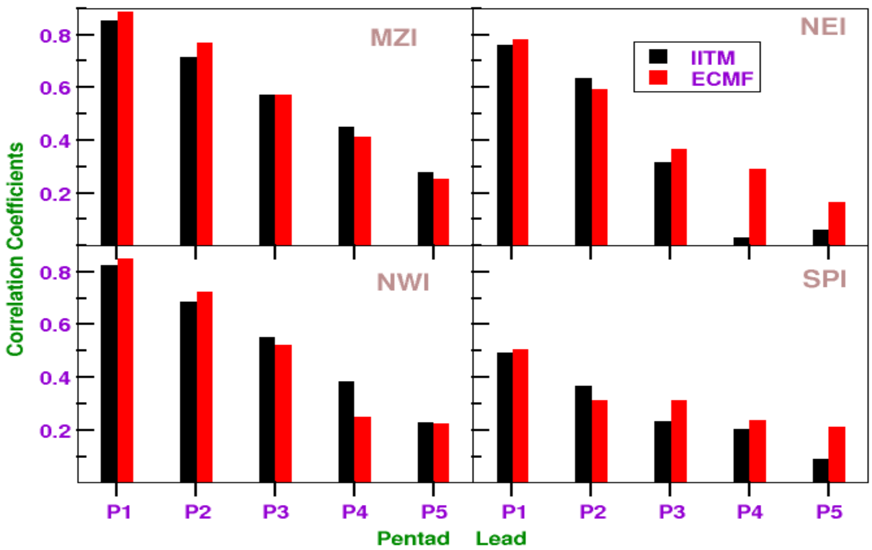


Figure 2: Skill of pentad (5-day average) rainfall anomalies at different pentad from IITM extended prediction system and ECMWF

- ✓ **Very high resolution (27km) weather forecasts at short and medium range resulting in gain of 2 days lead time.**

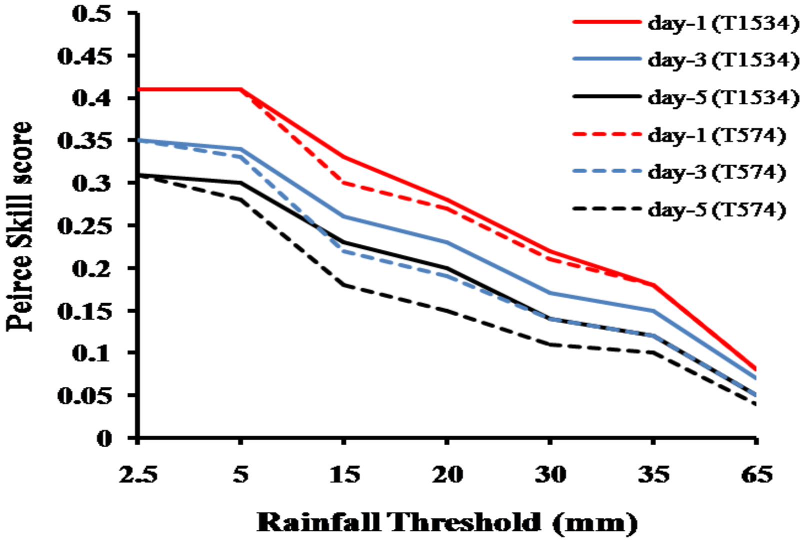


Figure 3: Skill score of 1, 3 and 5 day lead forecast of high resolution atmospheric model at lower (T574) and higher (T1534).

- ✓ **Development of a "Unified Model" (UM, adopted from UK Met. Office, UK) for high resolution short range & medium range forecasts. The efforts resulted in improving the prediction skill of short and medium range forecasts by 2 days. (e.g., The Critical Success Index (CSI) for monsoon rainfall (2-5 cm) over Core Monsoon Zone in Day-1 forecasts of 2007 and Day-3 forecasts of 2016 is 0.19, indicating an improvement in skill of rainfall prediction by 2 days for the cited CSI)**
- ✓ **Development of real time Global Forecast System for short range deterministic forecast at 12 km resolution**.
- ✓ **Developed data assimilation system using GODAS observations based on CFS-LETKF (Local Ensemble Transform Kalman Filter technique for the Ocean Model).**

- ✓ **Externally funded projects contributed to model developmental and diagnostic studies. Significant contributions are listed below:**
  a. Setting up of Ocean-atmosphere (weekly/strongly) Coupled data assimilation system based on LETKF for improving monsoon predictions.
  b. Multi-scale multi-cloud parameterization scheme was successfully implemented to improve the CFS model fidelity of monsoon weather and climate through better organized tropical convection.
  c. Improving multi-scale variability and interaction in a global coupled seasonal climate forecast system through embedded regional modelling at weather and cloud resolving scales.

d. Observational program over Bay of Bengal for identifying Coupled physical processes in the Bay of Bengal and monsoon air-sea interaction processes.
e. Improving Hindcast Skill of the CFS Modelling System by examining role of ocean in the Extended Range Prediction of Monsoon's Active Break Cycle.
f. Indian Monsoon Data Assimilation and Analysis.
g. Ocean-Land-Atmosphere Coupling and Initialization Strategies to Improve CFSv2 and Monsoon Prediction.
h. Understanding bias errors and addressing physics errors in the CFSv2 model to improve monsoon prediction.
i. Advancing Monsoon Weather-Climate Fidelity in the CFS through Improved Cloud-Radiation-Dynamical Representation.
j. Identification and Correction of Errors in Various Components of Dynamics and Physics of the Global Forecast System (GFS) Model.
k. Diurnal variability of summer monsoon rainfall in the UKMO Unified Model.
l. Evaluation and Improvement of the Unified Model for Short- and Medium-Range Prediction of Monsoon Rain Systems.
m. Bias estimation and effort for removal of bias in UM/ CFS coupled model output using adaptive techniques to improve forecast skill of ISMR.

Prediction systems developed under monsoon mission are transferred to IMD for operational use in 2017.

These achievements are resulted from;

Budget details of Monsoon Mission including HPC

(year wise break up)

Rs in Crores

	2012-13	2013-14	2014-15	2015-16	2016-17	HPC (total 5 yrs)	Total
Allotted	5.41	95.05	73.99	58.43	57.12	110.00	400.00
Actual received	3.91	16.00	23.55	27.60	11.66	103.02	185.74
Spent amount	6.72	11.59	24.33	21.49	18.49	101.13	183.75
Percentage	171%	72 %	103%	78%	158%	98%	98.9%

of funds utilized							

Prediction systems developed under monsoon mission are transferred to IMD for operational use in 2017.

❖ Background:

Indian summer monsoon is the lifeline of India, providing about 80% annual rainfall in a short span of four months from June to September and providing the necessary boost to the economy of the country. Indian summer monsoon rainfall (ISMR) has inter-annual as well as intra-seasonal variations and needs to be predicted well in advance for the benefit of the people and the Government of the country, especially for policy decisions with regard to agriculture, water management, etc. Thus, monsoon forecast is an indispensable need of the country for efficient management of agriculture, hydrology, power sector, disasters, etc. The forecasts should have sufficient skill, so that it can be believed by the users. For a long time, in India, Statistical models have been utilized for monsoon prediction, but these models have limited ability to predict extreme events. Coupled dynamical models were utilized for weather/climate predictions in advanced countries, having significant high performance computing resources for solving computationally intensive mathematical equations in a dynamic model but these models also did not have good skill for predicting ISMR. There are certain difficulties in forecasting monsoon properly, as the tropical ocean-atmospheric system is essentially chaotic; there are various fluctuations &interactions of the monsoon system at time scales ranging from days to decades, difficulty in modelling a realistic representation of the earth system processes, etc. To properly forecast monsoon, a realistic representation of the earth system processes, such as incoming solar radiation, winds, waves, tides, convection, clouds, soil, vegetation, topography etc. and interactions between them needed to be modelled using mathematical equations. Some of these processes are not well understood and observed and hence difficult to model – it was a real challenge for the scientists and it required coordinated research work. So, there was a need to have a mission mode programme in India, for producing skilful predictions of monsoon weather/climate using coupled ocean-atmosphere dynamical models.

In recent decades, dynamical numerical models have considerably improved and most of the global coupled models have good prediction skill of ENSO (El Nino Southern Oscillation) SST with six months lead time. The seasonal mean rainfall hindcast skill, at one season lead time, over the central Pacific is also very good. However, not much breakthrough has taken place in improving the prediction skill of Indian summer monsoon rainfall. In recent times, several new approaches (high resolution, super parameterizations, data assimilation, etc.)

have shown that the variability in tropics can be reasonably resolved, thereby creating a great scope for improving the monsoon prediction.

Climate models have made great strides in improvement over the past couple of decades and the prediction skill of seasonal rainfall over the El Nino Southern Oscillation in many of the dynamical models is above 0.7 (out of 1.0), however, the Asian monsoon rainfall (not Indian monsoon alone) prediction skill was below 0.1 in many of these coupled dynamical models. The success of prediction over the ENSO region indicated that there has been hope for dynamical models to predict the tropical climate including the Indian monsoon as most of the tropical climate variability is driven by slowly varying driver like the ENSO. However, failure of almost all models at that time indicated that there were some intrinsic problems of predicting the Indian monsoon rainfall. This indicated that a focused Mission Mode Program was required to make any progress in this direction.

In general the NWP systems of leading global NWP centres are extending the specific predictive skill of a prediction system by 1 day per decade. However proportionate improvement in skill was not noticed over the tropical monsoon region. The major international NWP centres have been able to invest adequate resources, both in terms of computing power and manpower for improving the skill of NWP. The improvements have been generally due to (a) Improvements in model dynamics and physics (b) Better observations (c) Careful use of forecast and observations, allowing for their information content and errors - achieved by variational assimilation e.g. of satellite radiances (d) Four Dimensional Data Assimilation (4D-VAR)/Hybrid Kalman filter, etc.

Therefore, a focused effort was required on the national scale for improving the assimilation and forecasting system, especially for the monsoon region, and this improvised the need to launch a **Mission mode project, called "Monsoon Mission".**

❖ Objectives of Monsoon Mission:

- ➢ To build a working partnership between the Academic and Research& Development Organizations, both national and international and the MoES to improve the monsoon forecast skill over the country.
- ➢ To setup a state of the art dynamical modelling frame work for improving prediction skill of (a) Seasonal and Extended range predictions and (b) Short and Medium range (up to two weeks) prediction.

Thus, the main objective of "Monsoon Mission" was to develop a skilful dynamical modelling system for the prediction of ISMR at (a) Short &Medium range (at least up to 10 days), extended range (up to 20 days) and long range (monthly to seasonal scale) and then to transfer this modelling system to India Meteorological Department (IMD) for delivering operational forecast to the nation.

❖ Major Achievements of the Monsoon Mission (Phase-1):

➢ **Dynamical modelling framework for improving the prediction skill of seasonal and extended range predictionswas successfully accomplished**.

Initially, IITM was given the responsibility to setup dynamical seasonal and extended range prediction system and recently the responsibility to setup ensemble prediction system for making short range forecasts was also bestowed on IITM. The main responsibility of the IITM was to use **CFS model of NCEP** as base model for setting up the above systems and to make developments on the base model, as this was one of the best ocean-atmosphere coupled model of the world for this purpose.

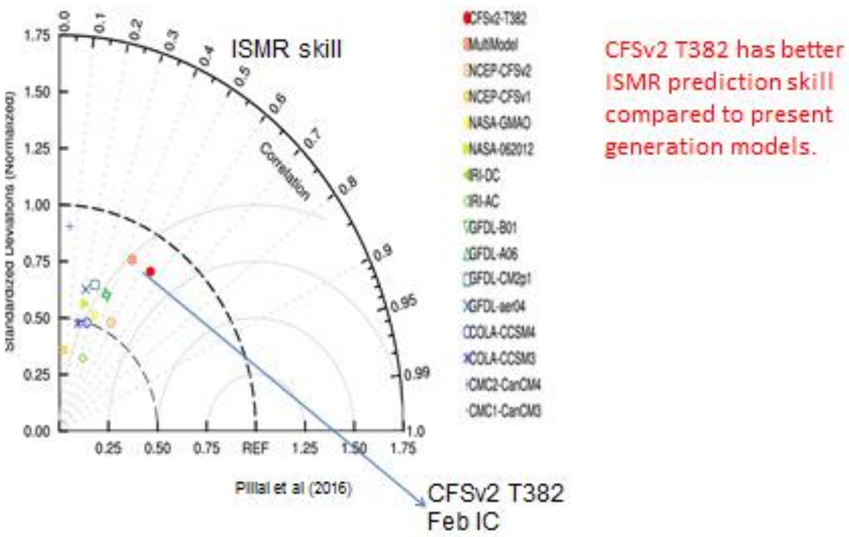


Fig. 1: Taylor plot showing that high resolution (T382) CFSv2 has better prediction skill for predicting Indian summer monsoon rainfall, compared to present generation models.

- **Very high resolution dynamical seasonal prediction system was setupwith improved prediction skill of monsoon over India.**Seasonal Prediction group of IITM started providing experimental real-time seasonal forecasts of the Indian Summer Monsoon (since 2011), as well as other major climate phenomenon such as El-Nino and Indian Ocean dipole (since 2015). These forecasts are based on the high resolution version of state-of-the-art Climate Forecast System Version 2 (CFSv2), which provides an atmospheric resolution of about 38 km in the horizontal. The forecasts are generated using an ensemble of minimum 40 members, which are initialized every calendar month using atmospheric initial conditions provided by ESSO-NCMRWF and the oceanic initial conditions provided by ESSO-IITM & ESSO-INCOIS. The model climatology is generated using 29-year hindcast runs which is ensemble mean of 10-12 members (depending on the calendar month used for initialization). The IITM seasonal prediction system with high resolution and model physics improvements demonstrated that seasonal prediction of Indian monsoon rainfall with useful skill (C~ 0.6) is realizable.

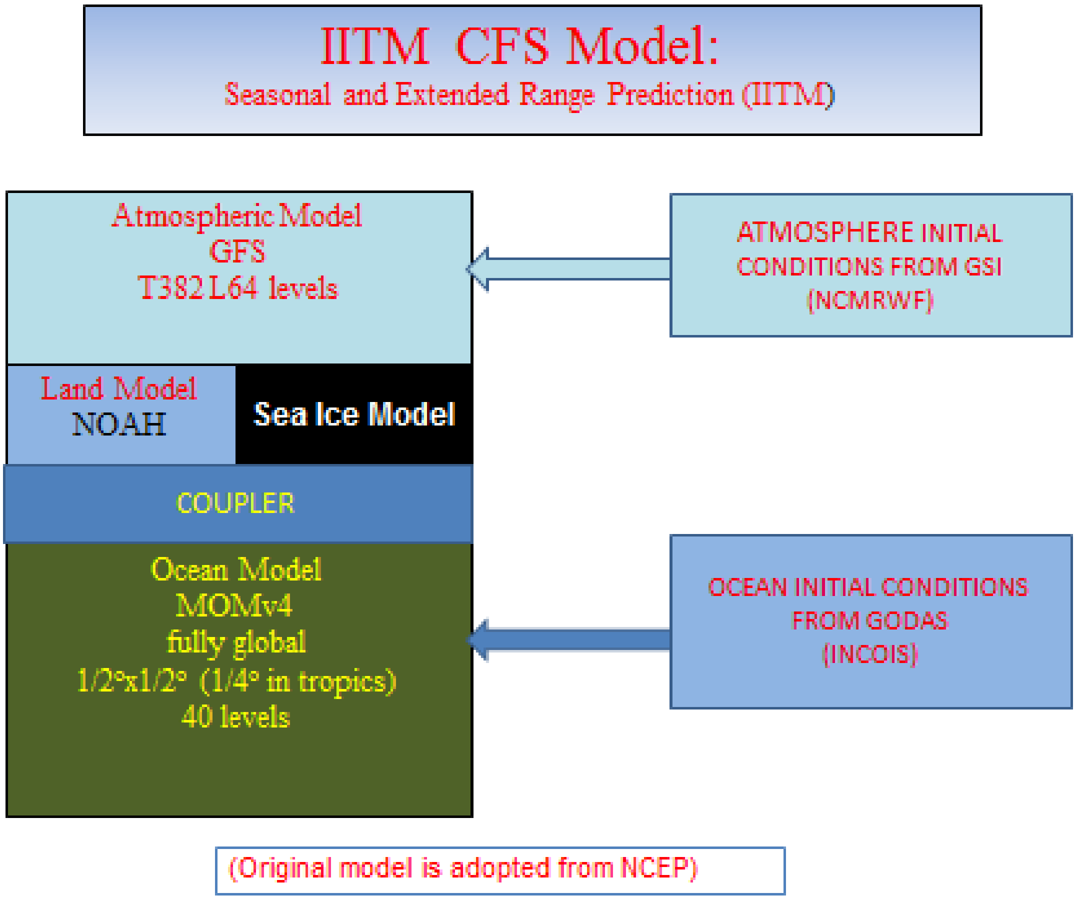


Fig. 2: Schematic diagram of **IITM CFS model.**

Using this prediction system, **India could predict 2015 drought** (i.e., below normal rainfall during 2015 SW monsoon season) with good accuracy when all other world leading climate centres were suggesting that it would be near normal monsoon during that year. This high resolution dynamic seasonal prediction system and its model outputs were shared with ESSO-IMD for their operational prediction and issuing Long range forecast to the country.

Recently, as an important Mandate of Monsoon Mission (Phase-1), **this indigenous version of the model has been transferred to ESSO-IMD** for their operational prediction activity and for issuing Long range forecast to the country. Recent predictions can be seen at the web-link: http://www.imdpune.gov.in/Clim_Pred_LRF_New/Models.html

- **IITM has been involved in various Model developmental activities.** These include **increase of horizontal resolution of the model**(Ramu et.al., 2016) from T126 Spectral (~ 100 km) to T382 spectral (~ 38 km) for the atmospheric component (GFS) of the CFSv2 and **improvements in parameterization of physical processes.**

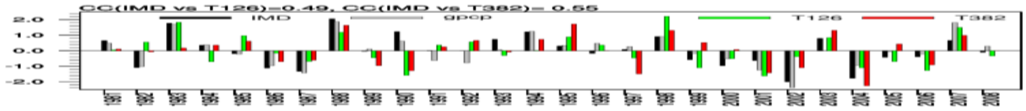


Fig. 3: Inter-annual variability of all India summer monsoon rainfall anomalies in **T126 and T382CFSv2**hindcast runs along with observations. Correlation between the IMD gridded rainfall and model-simulated rainfall averaged over the Indian subcontinent is given in the top left.

- There have been lot of **development activities** and efforts **forimprovements in parameterization of physical processes at ESSO-IITM**, especially improvements in convective parameterization (utilization of modified Revised SAS), cloud microphysics schemes, parameterization of Land Surface processes (including snow and sea-ice) and also application of super parameterization schemes, improvement in ocean model, etc. **Thesemodel developments have been useful to reduce the model biases and thereby showing some improvement in prediction skill.** These model developments have been successfullyimplemented in the Initial version of the Indian model to test the improvements in seasonal prediction skill.

ESSO-IITM wishes to increase horizontal resolution of the dynamical (ocean-atmosphere coupled) model CFSv2 further and wish to make further model developments to capture the regional aspects of rainfall & other meteorological parameters over different regions of the country with a good skill. Work is in progress but it requires more computational resources, which are expected to be available in coming years.

The integration of various recent model developments into this model is being coordinated by IITM at present and the integrated version (with recent and further model development) will subsequently be shared with ESSO-IMD (and finally can be transferred to ESSO-IMD).

- **CFS based Grand multi model ensemble (MME) prediction system has been setup for extended range prediction of the active/break cycles of monsoon** with reasonably good prediction skill over the country. Extended Range Prediction group of IITM has been providing experimental real-time forecast of the active-break spells of Indian Summer Monsoon Rainfall (since 2012) up to 4 pentad lead using an indigenously developed Ensemble Prediction system (EPS) based on the state-of-the-art Climate Forecast System Model Version 2 (CFSv2). The EPS generates a large number of forecasts from different initial conditions so that the expected forecast and also the expected spreads or uncertainties in terms of probability from this forecast can be informed. Forecast is generated after every 5 day interval since 16th May of the calendar year, for next 4 pentads (20 days) period (i.e., forecast lead time is up to 20 days and the updating is done in every 5 days interval). The pentad prediction skill may be considered as the intra-seasonal variability prediction skill and is a more rigorous way of evaluating the model's hindcast skill. Extended Range Prediction provides various products, like Prediction of Rainfall & low level winds, Chance of Heat wave (along with Maximum Temperature, etc.) up to 20 days in advance. The extended range forecasts are shared with agricultural community for their planning. Extended Range Prediction of Active/Break Spells (ERPAS) was certified for Quality Management System (QMS) compliant with the **ISO 9001:2008 standards** by the agency Standards Certification Council Pvt. Ltd. in the year 2015.The MME forecast are prepared using CFS (T126 & T382) and GFS(T126 & T382). Each resolution of CFS and GFS is having 11 ensemble members.

The **experimental real-time extended range prediction** (based on specific initial condition and predicted upto next 20 days from the initial date) were uploaded at the following web-link:http://www.tropmet.res.in/erpas/. MJO forecast and Predictions of various parameters, like Rainfall, Maximum & Minimum temperatures, soil moisture (0-10cm), Relative humidity and cyclogenesis were also available in the same link.

In addition to this, some aspects of large-scale Monsoon Intra-seasonal Oscillations are also studied. Predictions and verification have been done over 4 different homogeneous regions of India where ISMR is more or less homogeneous. The selected regions are Central India (CEI), North-East India (NEI), North-West India (NWI), South peninsula (SPI) and a broader region, monsoon core zone of India (MZI). Thus, one of the best prediction system in the world for predicting the active/break cycle of Monsoon was setup with moderate prediction skill.

Recently, **the experimental extended range prediction system** (from IITM) **has been transferred to IMD and operational forecasts will be available at IMD website** on weekly basis (on every Thursday).

- **IITM has setup high resolution T574 (Semi-Lagrangian core) Global Ensemble Forecast System (GEFS) for short range forecast with 21 ensemble member.** This system is being used to provide real-time short range ensemble forecast since June 2016. This forecast has been extensively used by IMD forecast offices at New Delhi and other centers during 2016 Monsoon months. A very high resolution T1534 (~11 km) deterministic forecast system has also been set up since August 2016 for short range predictions using GFS. Efforts are presently underway to setup ensemble prediction system based on GEFS at T1534 (~11 km) resolution as a commitment to Niti-Ayog and for this effort IITM, NCMRWF and IMD are working hand in hand.

Real time Global Forecast System for short range deterministic forecast: The ongoing (experimental) real time Short Range Deterministic Forecasting system based on GFS T1534 has been established in IITM and 8 days forecast based on daily 0000 UTC initial condition provided by NCMRWF is being disseminated to IMD by 15:00hrs. High resolution Global Forecast System (GFS) model at T1534 (Global horizontal resolution~12 km) has been run on real time daily (experimental basis) to generate deterministic forecast for 8 days. The forecast for 8 days is available at http://srf.tropmet.res.in/srf/files/archive_hires.php
The T1534 GFS forecast is found to capture the location and intensity of extreme rains and also the cyclogenesis with reasonably advance lead time. Presently initiatives are being taken to use the GFS T1534 forecast output for block level agriculture forecasting.

- Scientists have documented ocean/atmosphere model biases (through publications of various papers) and diagnosed potential direction for improvements in the modelling framework.

- **Coupled data assimilation system** based on **CFS-LETKF**(Local Ensemble Transform Kalman Filter technique for the Climate Forecast System) has been setup at IITM. The system at present is weakly coupled system. Efforts are on for setting up of coupled ocean-atmosphere data assimilation (strongly coupled) system at IITM, with active collaboration and coordination with University of Maryland, USA and ESSO-INCOIS.

- As an additional **important bonus and benefit** from the **Monsoon Mission CFS model**, the Centre of Climate Research (**CCCR** at IITM, Pune) developed an "Earth System Model" (**ESM**). This model has become **the first Indian model** to participate in Coupled Model Inter-comparison Project, Phase-6 (**CMIP6**) runs.

- **During last 5 years**, about**160 research papers were published under Monsoon Mission. About 130 of these are on CFS model diagnostics and developmental activities** - maximum number of whichwere published by MoES scientists, especially by IITM scientists**(Annexure-1). Many papers were published through funded projects (Annexure-2). On observational aspects 31 research papers** were published by scientists involved **in the Bay of Bengal observational Ocean Mixing and Monsoons (OMM) project (Annexure-2).**

- **Capacity building**: A significant number of early career scientists have been trained in model development and data assimilation through the MM efforts, initially via the Monsoon Desk and later through interaction in the collaborative projects building for the first time a critical mass of model developers in the country. During last 3 years, 10 MoES Scientists (5 from ESSO-IITM, 3 from ESSO-INCOIS and 2 from ESSO-NCMRWF) have been deputed abroad to get training and to work with Principal Investigators (world renowned scientists) of some International projects of the Monsoon Mission. For their deputations, funds were provided mainly from Monsoon Mission funds. There have been lot of benefits from these deputations for research & development in the field of Atmospheric & ocean sciences, both on weather and climate time scales.

- **Major Spinoff**: This capacity building has led to a major spinoff in the development of the first indigenous Earth System Model (ESM) in the country at IITM and made India ready to participate in the CMIP6 with our own model.

- **Technical advancement**: Monsoon Mission emphasized the need for **high-end HPC** not only for improved weather prediction, seasonal prediction and climate change projections but also for R & D to improve the existing skill of the models for all these set of predictions. By procuring and installing the **two high-end HPC (790 TF Aaditya HPC at IITM and 350 TF at NCMRWF)** under the MM, IITM demonstrated that indeed adequate computational infrastructure is an essential necessary condition for improved forecasts. IITM was also given the responsibility to manage the larger system and provide the computational facilities to all computations of IMD and INCOIS. By managing the computation needs of not only of IITM but also for IMD and INCOIS well in the HPC, IITM has shown maturity in managing such large HPC system in the country. We believe, this is also a spinoff achievement.

- **ESSO-NCMRWF** contributed significantly for model development works on “Unified Model” (**UM**, adopted from UK Met. Office, UK) for **high resolution short range & medium range** forecasts.

- **ESSO-INCOIS** contributed significantly for improving **GODAS** analyses with additional data over Indian seas through their ocean data observations and assimilation system.

Thus, **Monsoon Mission has led to impressive development activities and improvement of forecasting system during past 5 years and it resulted in operationalization of dynamic models for seasonal and extended range prediction of Indian monsoon and related weather phenomena**. In addition to the progress made by MoES organizations, a lot of **good work has been carried out by various national and international projects**, funded by Monsoon Mission. These works include diagnosing the model biases, carrying out model development activities, etc. A brief of these Monsoon Mission projects have been given below.

❖ Funding of National and International projects:

For buildinga working partnership between the Academic and R& D Organizations, and the MoES organizations (IITM, IMD, NCMRWF), several national and international projects were funded through Monsoon Mission, after appropriate review by SRMC and approval by SSC of the Monsoon Mission. Till now, a total of about **40 projects**(including National and International projects) have been funded by MoES, through Monsoon Mission. Out of these, 20 International projects (from different countries, like USA, UK, Australia, Canada, France, Japan & UAE) have been funded, mainly for modelling aspects. Most of the National projects (13) were based on modelling aspects, whereas an observational project over Bay of Bengal was undertaken by I. I. Sc., Bangalore; also, 3 subprojects ofBay of Bengal observational project were approved and were funded through Monsoon Mission. In addition, there are 3 India-UK collaborative (MoES-NERC) projects, related to observational aspects. These collaborative projects (SWAAMI, INCOMPASS & BOBBLE) were initiated by IISc, Bangalore to carry out observational campaign and IITM was involved in these projects. For smooth implementation and execution of Monsoon Mission activities (especially for monitoring and coordinating the National & International projects of the Monsoon Mission), a Monsoon Mission Directorate (MMD) was established at ESSO-IITM, Pune. The Directorate makes arrangements of organizing meetings of Scientific Review & Monitoring Committee (SRMC) for review of the projects and sending the SRMC recommendations to Scientific Steering Committee (SSC) of Monsoon Mission for approval of projects. After approval, Sanction letters are issued to Project PIs and MMD coordinates the release of funds to different projects through ESSO-IITM administration. MMD also helps in organization of various high level meetings and training workshops through Monsoon Mission funds. Whenever required, it communicates with Program Director, MoES for various activities and funding related matters.

❖ Working Structure of the Monsoon Mission: (Details in Annexure-3)

International and National projects, funded by Monsoon Mission:

International (Foreign) Projects				
Sr. No.	**Name of University/Organization**	**Name of PI**	**Project Title**	**Country**
1	LOCEAN-**IPSL**, University Pierre and Marie Curie, Paris, France	Prof. Terray Pascal	"Impacts of ocean-atmosphere coupling and SST high frequency variability on the coupled simulation of the mean state and variability of the Indian Summer Monsoon"	France
2	George Mason University (**GMU**), USA&**NCEP**, USA	Dr. James Kinter	"Ocean-Land-Atmosphere Coupling and Initialization Strategies to Improve CFSv2 and Monsoon Prediction"	USA
4	CAWCR, Bureau of Meteorology (**BoM**), Australia	Dr.Elizabath Ebert	"Evaluation and Improvement of the Unified Model for Short- and Medium-Range Prediction of Monsoon Rain Systems"	Australia
4	Florida State University, (**FSU**) USA	Dr. Ruby Krishnamurty	"Use of observations defining upper ocean processes in the Bay of Bengal towards improved weather/ seasonal forecast"	USA
5	University of **Miami**, USA	Dr. Brian Mapes	"Understanding bias errors and addressing physics errors in the CFSv2 model to improve monsoon prediction"	USA
6	**Imperial College**, London, UK	Dr. Ralf Toumi	"Stochastic Parameterization and Forecasting of Wind Energy in India"	UK
7	Florida State University, (**FSU**) USA	Prof. T. N. Krishnamurti	"Sensitivity Studies for Indian Summer Monsoon Forecast Modeling"	USA
8	University of **Reading**, UK	Dr. Andrew Turner	"Improved Indo - UK capability for seamless forecasting of monsoon rainfall: from days to the season"	UK
9	University of **California**, USA	Dr. Dune Waliser	"Advancing Monsoon Weather-Climate Fidelity in the NCEP CFS through Improved Cloud-Radiation-Dynamical Representation"	USA

10	University of **Victoria**, Canada	Dr.BouleamKhouider	"An approach of Multi-scale multi-cloud parameter-zation to improve the CFS model fidelity of monsoon weather and climate through better organized tropical convection"	CANADA
11	University of **Maryland,** USA	Dr. Arun Kumar	"Understanding the role of sea surface temperatures in the simulation and prediction of the monsoon intra-seasonal oscillation"	USA
12	University of **Maryland**, USA	Prof. Raghu Murtugudde	"Role of the Atmosphere and the Indian Ocean in the Evolution of Monsoon-ENSO Tele-connections in CFS"	USA
13	University of **Hawaii**, USA	Dr. H. Annamalai	"Extended Monsoon Episodes: Understanding Processes and Pathways for Improved Prediction in CFSv2"	USA
14	University of **Maryland**, USA	Prof. Eugenia Kalnay	"Improving Monsoon Predictions with a Couple Ensemble Kalman Filter Data Assimilation System"	USA
15	New York University (**NYU**), Abu Dhabi, UAE	Dr.Ajaya Mohan Ravindran	"A novel approach for improving rain-gauge data assimilation and extended range prediction of sub-seasonal variability over India."	Abu Dhabi, United Arab Emirates
16	Florida State University(**FSU**), USA	Dr.VasubandhuMisra	"Regionally coupled ocean-Atmosphere seasonal hindcasts of the Indian summer monsoon at 10 Km resolution"	USA
17	**Purdue** University, USA	Prof. Dev Niyogi	"Improved under-standing and representation of land surface processes for short, medium and long range prediction of monsoon rainfall"	USA
18	University of **Colorado** at Boulder, USA	Prof.Weiqing Han	"Indian Ocean air-sea interaction Processes and their Effects on Indian Summer Monsoon Intraseasonal Variability: with implication for improving CFS2 monsoon forecast"	USA
19	Met Office, U.K. (**UKMO**)	Prof. Dale Barkar/ Dr. Richard Renshaw	"Indian Monsoon Data Assimilation and Analysis"	UK
20	University of **Aizu**, Japan	Dr.Saji N. Hameed	"Improving multi-scale variability and inter-actions in a global coupled seasonal climate forecast system through embedded regional modeling at weather and cloud resolving scales"	Japan

National (Indian) Projects

Sr. No.	Name of University/Organization	Name of PI	Project Title
1	**C-DAC, P**une	Mr. Abhishek Das	"Portable CFS model with Performance Optimization and Enhanced Usability"
2	Cochin Universityof Science and Tech. (**CUSAT**), Kerala	Mr. Baby Chakrapani	"Role Of Ocean In The Extended Range Prediction of Monsoon's Active Break Cycle -Improving Hindcast Skill of The NCEP-CFS Modelling System"
3	**IISC** -Bangalore	Prof.DebasisSen gupta*	"Coupled physical processes in the Bay of Bengal and monsoon air-sea interaction" **(Bay of Bengal Project)***
4	**IISC** -Bangalore	Dr.Arindam Chakraborty	"Identification and Correction of Errors in Various Components of Dynamics and Physics of the Global Forecast System (GFS) Model"
5	**CDAC-B**angalore	Dr. S. Janakiraman	"Portable version of CFS model for the monsoon mission".
6	Andhra University (**A.U.**), Visakhapatnam	Dr. S. S. V. S. Ramakrishna	Understanding the biases in the Climate Forecasting System model 1. Sea Surface Temperature (SST) 2. Intensity and tracks of monsoon depressions and cyclones for the Monsoon - Indian Ocean domain"
7	University of **Allahabad**, U.P.	Dr.ShailendraRai	"Predictability of intra-seasonal oscillatory modes and ENSO-monsoon relationship in NCEP CFS with reference to Indian & Pacific Ocean"
8	University of **Allahabad**, U.P.	Dr.SuneetDwive di	"Improved Ocean Initialization for Coupled Modelling for week-2 Monsoon forecast"
9	University of **Calcutta** (**C.U**.), Kolkata, West Bengal	Prof.SutapaChau dhuri	"Bias estimation and effort for removal of UM/ CFS coupled model output with adaptive techniques for improving forecast skill of Indian summer monsoon"
10	The Energy & Resources Institute (**TER**I), New Delhi	Dr. M. S. Madhusoodanan	"Diurnal variability of summer monsoon rainfall in the UKMO Unified Model"
11	**NAL**, Bangalore	Dr. G. Mrudula	"Development of standalone Boundary Layer Module for National Monsoon Mission"

12	**IISC**, Bangalore	Dr.Arindam Chakraborty/ Ajaya Mohan Ravindran	"A novel approach for improving rain-gauge data assimilation and extended range prediction of sub-seasonal variability over India."
13	**IIT-B**hubaneshwar	Prof.U.C. Mohanty/ Prof. Dev Niyogi	"Improved under-standing and representation of land surface processes for short, medium and long range prediction of monsoon rainfall"
14	**IISC** -Bangalore	Arindam Chakraborty/ Dr. Ralf Toumi	"Stochastic Parameterization and Forecasting of Wind Energy in India"

Sub Projects of Bay of Bengal Project*(With Prof.DebasisSengupta, IISC)			
Sr. No.	**Name of University**	**Name of PI**	**Project Title**
1	**IIT M**adras	Dr.ManikandanMathur	“Coupled physical processes in the Bay of Bengal and monsoon air-sea interaction”
2	**CSIR-V**ishakhapatnam	Dr.V.S.N.Murty	“Coupled physical processes in the Bay of Bengal and monsoon air-sea interaction”
3	**TIFR-H**yderabad	Prof. Rama Govindarajan	“Coupled physical processes in the Bay of Bengal and monsoon air-sea interaction”

MoES (India)- NERC (UK) Collaborative Projects		
Name of University	**Name of PI**	**Project Title**
IISC, Bangalore	Prof. G.S.Bhat	"Monsoon dynamics and thermodynamics from land surface, through convection to the continental-scale (INCOMPASS)"
IISC, Bangalore	Prof.S.K.Satheesh	"South West Asian Aerosol Monsoon interaction (SWAAMI)"
IISC, Bangalore	Prof. P.N.Vinayachandran	"Impact of ocean-atmosphere processes in the Bay of Bengal om the South Asian monsoon (BOBBLE)"

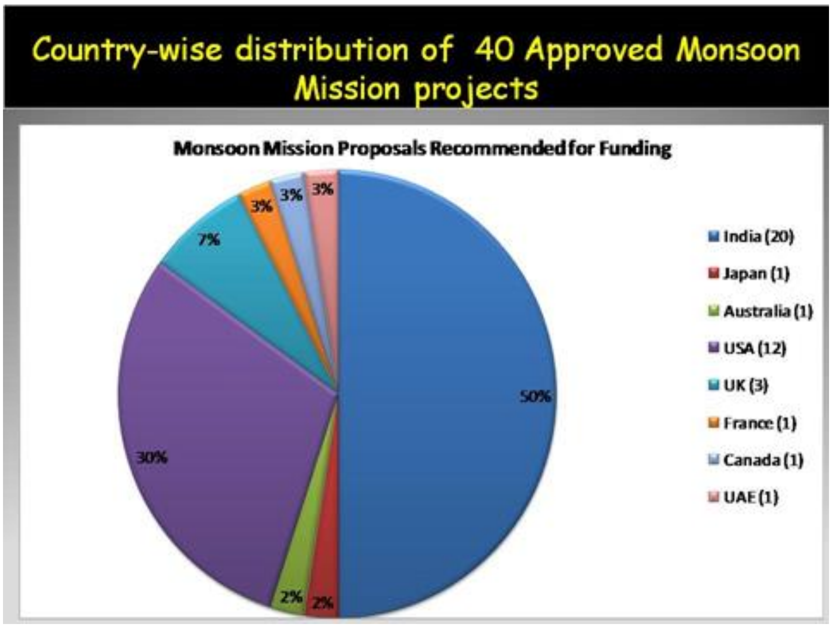


Fig. 4: Country-wise distribution of approved Monsoon Mission projects

❖ **Working partnership has been established between the Academic and R & D Organizations, both national & international and the MoES** to improve the monsoon forecast skill over the country.

- **Partnership among MoES organizations :** MoES organizations share the responsibility of making seasonal, extended range & short range predictions as follows

Preparation of Initial Conditions (ICs): Atmosphere →NCMRWF ; Ocean →INCOIS

Prediction/Hindcast runs: Seasonal and Extended range prediction→ IITM;

Short range → IMD/IITM/NCMRWF ; Medium range →NCMRWF

- **Partnership with other organizations :**

Model developmental activity on **CFS/GFS→** NCEP/IITM/GMU/Univ. of Victoria/FSU/IPSL /Purdue Univ./NAL

Model developmental activity on**UM→** UKMO/NCMRWF/BoM/

Data Assimilation research/development,**CFS based→** IITM/INCOIS/Univ. of Maryland

Data Assimilation research/development, **UM based→** UKMO/BoM/Allahabad Univ./Met. Office

Model diagnostics/biases: IITM/IISc./A.U/CUSAT/C.U/Allahabad/TERI/Univ. Maryland /NYU/FSU/Univ. Aizu/Univ. Miami/Univ. Rading/UCLA/IPRC/Univ. Colarado

Observational support: IISc./IITM/INCOIS/IMD/NCMRWF

❖ Contributions from National projects funded by Monsoon Mission:

➢ Portable CFS model with Performance Optimization and Enhanced Usability

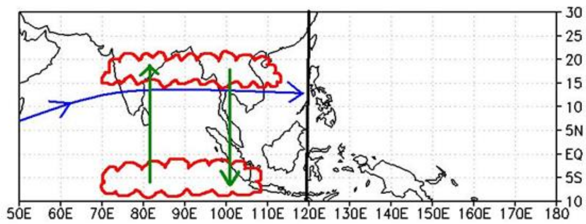
Mr. Abhishek Das(PI) and his team (of C-DAC, Pune) have successfully completed this project on portability of CFS model and its performance optimization for enhanced usability of the model. They worked meticulously, in coordination with IITM scientists and completed various experiments on the code configuration of the model, including testing for higher version of ocean model (MOM5), various coupling configurations, etc. While reviewing this project, SRMC appreciated their work and suggested that integrity& performance evaluation and its acceptability may be independently evaluated and the results may be examined with a relatively higher period of model integration (at least 60-90 days integration).

➢ Portable version of CFS model for the monsoon mission

Dr. S. Janakiraman (PI) and his team (of CDAC-Bangalore) completed the project for preparing a portable version of CFS model to a popular open source Linux operating system, so as to broaden its usage. It may be noted that the exercise of porting to another platform makes the software robust. They also prepared a technical documentation of CFS version-2, which may be useful for users as an "User Manual" from the software point of view. An extension was provided to them for completion of their objectives.

➢ Role of Ocean in the Extended Range Prediction of Monsoon's Active Break Cycle - Improving Hindcast Skill of the NCEP-CFS Modelling System

Prof. B. Chakrapani (PI , CUSAT, Cochin) and his team (including Co-PIs, **Prof.P.V.Joseph**, CUSAT, and **Dr. M.R. Ramesh Kumar**, NIO, Goa) examined whether the ocean variability in monsoon season is realistically reproduced in the CFS coupled model runs (collected from IITM), particularly the Mixed Layer Depth (MLD) and SST variations on the time scale of the Active-Break cycle in normal, La Nina and El-Nino years. They also studied the air-sea fluxes of heat in relation to the Active-Break cycle. They proposed the following hypothesis (**Fig. 5**):



In La Nina, the LLJ is over Asian continent only and the convection is confined to west of 120E fluctuating between equator and 20 N. In the absence of convection Pacific box SST increases steadily. In CFS, since MLD is only 20m the rate of increase of SST (mixed layer temperature) is much larger than climatology

Hypothesis

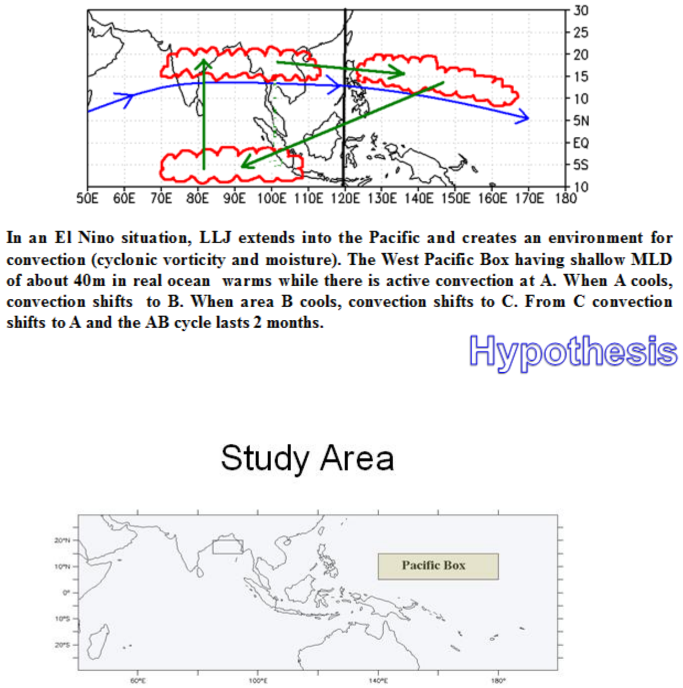


Fig. 6: Study area for validating their hypothesis

The study area for validating their hypothesis is shown in the above figure. They plotted the difference of QUICKSAT surface winds for El-Nino years (2002, 2004, 2009) and Non-El Nino years (2000, 2001, 2003, 2005, 2007 & 2008) and showed significant difference over the Pacific box. They also analysed the model Bias in MLD over the study region both from CFS output and Hadley reanalysis. They showed the difference in patterns of Latent heat flux, Net heat flux, Shortwave radiation flux etc. for 1998 and 2004, using model output and observed values. They found that **CFS V2 simulates a relatively Shallow MLD.** They diagnosed following reasons for the Simulation of Shallow MLD of the CFS V2 :

(a) Anomalies in the simulation of wind by the atmospheric component

(b) Vertical diffusion scheme of the ocean component

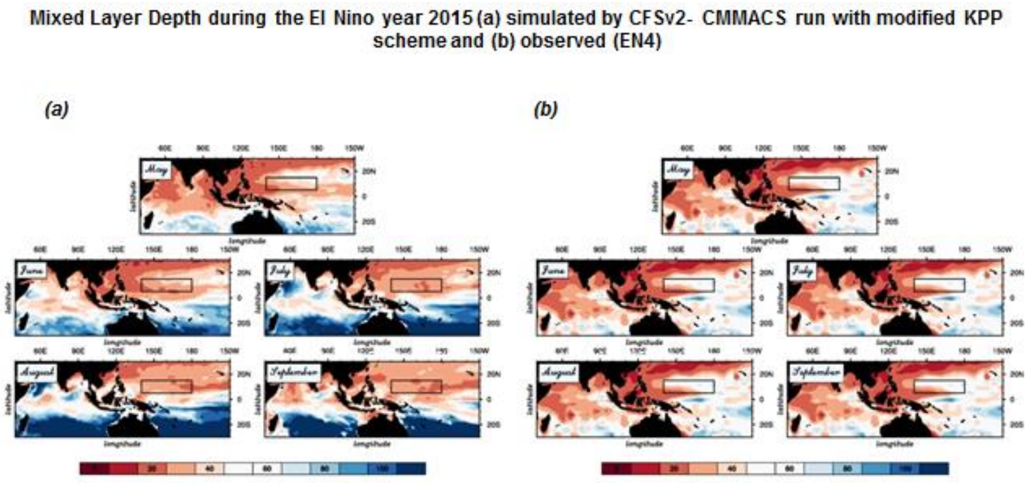


Fig. 7 : Mixed Layer Depth during El-Nino year 2015

For improving MLD simulation, it has been suggested to include the non-breaking surface wave-induced vertical mixing in KPP (as in Li et al., 2013) in the present CFS modelling system.

- **Coupled physical processes in the Bay of Bengal and monsoon air-sea interaction(Bay of Bengal observational Project)**

Prof. Debasis Sengupta(Professor, IISc - Bangalore)and**Dr. M. Ravichandran** (earlier at INCOIS-Hyderabad and now Director, NCOAR- Goa) are the PIs of this important observational project over Bay of Bengal. Following important persons are involved in this project as Co-PIs and PIs of its subprojects : Prof. G. S. Bhat, IISc;Dr. Jai Sukhatme, IISc; Dr. V. Venugopal, IISc; Dr. R. Venkatesan, NIOT- Chennai, Dr. V.S. N. Murty, NIO- Vishakhapatnam ; Dr. Rashmi Sharma, SAC- Ahmedabad; Dr. Rama Govindarajan, TIFR-Hyderabad; Dr. Manikandan Mathur, IIT Madras & Dr. Sathyanarayana Ayyalasomayajula, IIT- Bhubaneswar. For brevity, this project is often referred as "**Ocean Mixing and Monsoons" (OMM)**.

The main objectives of this project are: (I) To gather fine-scale observations in the near-surface Bay of Bengal across seasons, (II) To create a reference dataset on high-resolution surface fluxes and subsurface oceanography from the Woods Hole Oceanographic Institution (WHOI) Air-Sea Interaction Met (ASIMET) Moorings; (III) To build capacity in fine-scale observation and modelling through international collaboration. Specific science objectives are to understand : (a) pathways of near-surface freshwater; (b) mesoscale (order 100 km) and sub-mesoscale (order 1-10 km horizontal scale) structures: filaments, eddies, fronts; (c) key sub-mesoscale processes of upper ocean mixing and stratification; (d) influence of near-surface freshwater and salinity stratification on upper ocean thermodynamics; (e) air-sea gradients, atmospheric boundary layer and surface fluxes; and (f) air-sea coupling on diurnal to sub-seasonal scales. The approach in the mature stage of the project is synthesis of fine-scale observations and models. The work under this programme is expected to lead to improved parameterisation of air-sea fluxes and upper ocean physics in ocean models and coupled models used for diurnal to sub-seasonal monsoon prediction. OMM has gathered a rich dataset from moorings and key ship-borne and autonomous instruments such as gliders and Lagrangian floats. US collaborators have shared with OMM PIs some of their diverse data from ships, autonomous instruments and an air-sea flux mooring. The team is in constant coordination with IITM Scientists to see how the Bay of Bengal field observations and emerging process insights can be used for physical process-based diagnostics (of biases) in ocean and coupled models being run at IITM.

The main outcomes so far are: Physical and human capacity has been developed at INCOIS for fine-scale (1 km horizontal resolution) observations of the near surface ocean from ship-borne and autonomous instruments such as gliders and water-following Lagrangian floats, as well as high-resolution surface fluxes from moorings at NIOT. Our observations have led to a major advances in knowledge of fine-scale variability and physical processes in the shallow oceanic boundary layer. This warm, low-saline, gravitationally stable layer makes the north Bay of Bengal so responsive to surface forcing. The first research cruises have been executed with adaptive planning based on real time in situ data from ship and floats, and inputs from satellites and models. OMM has made the first fine-scale (300 to 1500 m horizontal resolution) upper ocean observations from research ships in the Bay of Bengal, with underway CTD and acoustic Doppler current profiler (ADCP)-differential GPS. As part of collaborations, OMM has obtained the first 13-month record of quality, high-resolution surface flux and subsurface ocean dataset in the Bay of Bengal, from a WHOI ASIMET mooring (see below) at 18.01N, 89.45E. NIOT and INCOIS personnel have been trained in sensors, data quality and analysis of ASIMET data. Three other moorings in the vicinity are maintained by NIOT and INCOIS ("Bay of Bengal Observatory"). OMM has obtained the first datasets from a Sea-glider and a water-following Lagrangian float in the north Bay of Bengal – basic infrastructure for autonomous instruments has been setup at INCOIS, and INCOIS personnel have received training at Kongsberg Inc. and the Applied Physics lab. (APL), University of Washington, to deploy and operate both instruments and analyse data. **The science focus** so far has been on (i) origin and sustenance of persistent, shallow salinity stratification in the north Bay of Bengal; (ii) shallow ocean boundary layer and shallow momentum trapping; (iii) near-inertial oscillations, shear-generated turbulence and internal waves in the presence of shallow stratification; (iv) relation of the shallow boundary layer to sub-seasonal variability of sea surface temperature (SST), mixed layer depth, and upper ocean thermodynamic structure; (v) diurnal to sub-seasonal surface fluxes, upper ocean advection, heat and fresh water balance; (vi) ocean optics, turbidity, chemistry and biology relevant to thermodynamics, and a beginning has been made on (vii) air-sea coupling on diurnal to sub-seasonal scales.OMM has acquired nearly 5000 line kilometres of upper ocean measurements from Indian research ships with order one kilometre lateral resolution in summer, autumn and briefly in winter.

Major finding includes discovery of **salinity-dominated sub mesoscale (order 1-20 km) fronts**, and found evidence that **lateral processes at fronts actively stratify the near-surface ocean.** Other significant results are in the areas of shallow momentum trapping and subsurface penetration of near-inertial oscillations and "squeezed" Ekman flows; internal waves; pathways of surface freshwater; heat and salinity balances on 100 km and 10 km scales using a glider-mooring combination, the first Lagrangian view of upper ocean mixing, and development of a satellite-based daily surface flux dataset and near-surface velocity dataset.

- **Identification and Correction of Errors in Various Components of Dynamics and Physics of the Global Forecast System (GFS) Model**

Dr. Arindam Chakraborty (PI from IISc, Bangalore) and his team examined various components of Dynamics and Physics of the Global Forecast System (GFS) Model (which is the atmospheric component of CFS model) in details and identified error components in various fields and made computations for corrective measures.

- **Understanding the biases in the Climate Forecasting System model : 1. Sea Surface Temperature (SST); 2. Intensity and tracks of monsoon depressions and cyclones for the Monsoon - Indian Ocean domain**

Dr. S. S. V. S. Ramakrishna (PI, Andhra University, Visakhapatnam) and his team used GFS& CFS Outputs to find the errors in the track and intensity of tropical cyclones and monsoon depressions and to assess the ability of CVSv2 model in reproducing the monsoon rainfall. For this study, they used the CFS model outputs (obtained from IITM, Pune) of5ensembles (namely, 00hrsof5th,10th,15th,20thand25thofFebruary, from1995to2012hindcastrunsand2013&2014Forecastdata were also used. They analysed water vapour parameters (like, water vapour transport, moisture flux convergence) in CFSv2 model output and compared with NCEP FNL model output and validated those with IMD data and the results were published. They found that themoisturefluxconvergencefieldsinbothCFSandFNLmodeloutputsdonotshowgoodagreement withtheobservedrainfallpatternsbothinintensityandspatialextent.They also examined SST Bias in the CFSV2 Model output for the Monsoon period, by comparing with observed TMI SST over the tropical Indian Ocean for the years 1998-2011. They presented evidence for two representative cases for strong positive and strong negative SST bias after identifying 20 cases for strong positive and strong negative SST bias.

- **Predictability of intra-seasonal oscillatory modes and ENSO-monsoon relationship in NCEP CFS with reference to Indian & Pacific Ocean**

Dr.Shailendra Rai (PI from University of Allahabad, U.P.) and his team (including Prof. Avinash C. Pandeyand Dr. Suneet Dwivedi) collaborated with IITM scientists (Dr. A. K. Sahai's group) in this project, for prediction of daily modes of South Asian monsoon variability and its association with Indian and Pacific Ocean SST in the NCEP CFS v2 and for prediction & error growth in the daily forecast of precipitation from the NCEP CFSv2 over the subdivisions of Indian subcontinent. They also made an analysis of the impact of SST drift in the ECMWF system 3 on simulation of the Indian summer climatology and Seasonal prediction skill of Indian summer monsoon rainfall in ECMWF system 4 model. They worked on Seasonal prediction of ISMR and its relationship with EL–NINO and IOD in ECMWF system 4 coupled model. They are also studying South Asian monsoon variability on intra-seasonal time scale in the latest version of NCEP CFS.

- **Improved Ocean Initialization for Coupled Modelling for week-2 Monsoon forecast**

Dr. Suneet Dwivedi (PI, K. Banerjee Centre of Atmospheric and Ocean Studies, University of Allahabad, Allahabad, UP) and his team worked on the following objectives : (a) Development, configuration and execution of Indian Ocean State Estimation system using Ocean component of Unified Model (UM) of UK Met Office and its associated Data Assimilation scheme (viz. NEMO & NEMOVAR); (b) Generation of quality controlled four-dimensional (three-dimensional time varying) geophysical state of the Indian Ocean (with emphasis on ocean's upper hydrographic/thermal structure and flow field) and (c) Providing coherent estimates of space-time varying upper Ocean mixed layer depth. Their study included Indian Ocean Modeling around Arabian sea &Bay of Bengal, using NEMO-AGRIF (combination of Global and Local modeling); 3-D time evolving flow field and hydrographic structure of the region [70-95E;0-20N] during 1996-2007 (12 years) at 25 km resolution, and Upper Ocean mixed layer depth variability. They worked on Customized Regional Indian Ocean Modeling using NEMO model and made comparison of vertical sub-grid scale parameterization schemes (TKE vs. KPP). They utilized a very High-Resolution (5 km) regional modeling in support of Cyclone Hudhud and carried outlimited area high-resolution modeling in the Bay of Bengal. They also worked for Customization and development of NEMOVAR setup in final stages at their University (UoA). Rose, Cylc, FCM Make have been successfully installed at local servers; NEMO & NEMOVAR executables are being generated; Restart files and ancillary data are being available. NEMOVAR output will be generated.This project was an useful initiative in carrying out experiments using state-of-the-art ocean GCMs. The prototype NEMOVAR assimilation setup may be used for process oriented expeditions in real time alongwith giving better ocean initializations.

- **Bias estimation and effort for removal of UM/ CFS coupled model output with adaptive techniques for improving forecast skill of Indian summer monsoon**

Prof. Sutapa Chaudhuri (PI, University of Calcutta, Kolkata, West Bengal) an her team worked on the project objectives, mainly to improve the prediction of various components of Indian Summer Monsoon (ISM) utilizing observations, theory and the results of CFSV2 / UKMO model, by the **method of bias correction and error minimization**. The analyses of predictability errors also play significant roles in error modification and bias correction in simulating CFS besides the forecast error. Their performed study and analysis of various components of monsoon and their seasonal and monthly variability (spatial and temporal) during June, July, August and September (JJAS) of SW monsoon, addressing Seasonal variability of monsoon and Correlation analysis between monsoon rainfall and various components like SST anomaly, ENSO, NAO, etc. They worked on Predictability of the active or break phases and intra-seasonal variability, using Empirical Orthogonal Function

(EOF) analysis and identification of relevant predictors using Principal Component Analysis (PCA). Their work included implementation of various methods (like ARIMA, power regression, neural networks, ensemble neural network, genetic algorithm, rough set theory, intuitive fuzzy logic, Ampliative reasoning, simulated annealing, etc.) for model generated error estimation and correction pertaining to the onset of monsoon, monsoon rainfall, draught or flood year, alongside CFS simulation. Error analyses for both CFS (v2) and Unified model (UM) of UKMO generated products were carried out and their comparison was made. They found that the model bias arises due to various mesoscale weather components, which can be taken care of using Ensemble Kalman Filter (EnKF) or any other methods. They also attempted performance analysis of model outputs using various skill scores, and Error minimization of the model products. Scrutinizing the validation of model after bias correction and error minimization was also done.

- **Diurnal variability of summer monsoon rainfall in the UKMO Unified Model**

Dr. M. S. Madhusoodanan (PI: The Energy & Resources Institute, TERI, New Delhi) and his team studied the diurnal variability of summer monsoon rainfall in the UKMO Unified Model. The Characteristics of diurnal variation of summer monsoon rainfall (JJAS) over India and neighbouring regions were studied using TRMM3B42 3-hourly data, Global forecast Model (GFS) and UKMO Unified Model for 2 years (2013-2014). For analysing diurnal variation of rainfall, harmonic analysis was done. The different regions selected for diurnal variation study are the monsoon core region of Central India, Foothills of Himalayas, West coast of India, Northeast India and Bay of Bengal. In the TRMM3B42 observation, the peak rainfall observed in early morning hours (0230-0530IST) over Bay of Bengal and the coastal regions. There are multiple modes of the peak octet of diurnal rainfall at 1130hrs, 1430hrs and 1730 hrs.IST moving southwards from Head bay. West coast of India and Foothills Himalayas were found to have an early morning rainfall (0230 IST).Central India receives maximum rainfall at 1730 IST. The UKMO unified model is unable to reproduce the observational (TRMM3B42) diurnal variation in precipitation (peak-time) over Indian land mass. The model simulates an early peak (6-12 hours earlier) in rainfall over all the domains over India as compared to the observations. The unified model also shows large difference in amplitude when compared to observations. The GFS model is able to simulate the diurnal variation of rainfall (peak time) relatively better than the UKMO Unified model over the land and ocean mass. This model also simulated an earlier peak (3-4 hours earlier) as compared to observation over Central India and Bay of Bengal. Over southern Peninsular India, North East India and Foot Hills of Himalayas. However, over the west coast of India, the GFS model shows large phase difference in maximum rainfall. It is also observed that day-1 to day-3 forecasts in both models (GFS and UM), the pattern of phase (rainfall peak hours) remains more or less the same. For both observations and models : The variance of rainfall amplitude explained by first harmonic shows that the diurnal cycle is the most prominent in the observed frequency and it explains about 85 % of the total variance over most of the country in both models. The semi diurnal cycle has smaller amplitude than the diurnal cycle and it explains most of the remaining variance .The rest of the cycles seems unimportant as their amplitude are small and the amount of variance explained by them are negligible. To investigate the phase and amplitude difference in the model simulated diurnal rainfall, further analysis was carried out over the variables like T2m, surface pressure and specific humidity. The model simulated (GFS and UM) temperature at 2m, surface pressure and specific humidity over most of regions are in phase with observation (MERRA). The role of local convective instability was also studied by diagnosing CAPE and moist static energy. By theory the peak in CAPE magnitude is expected to lead precipitation peak by 0-4 hours. For the GFS model CAPE is roughly in phase with rainfall over most regions. These patterns however are not clearly observed in UM model. CAPE and rainfall is out of phase over all regions in UM model.

- **Development of standalone Boundary Layer Module for National Monsoon Mission**

Dr. G. Mrudula (PI, NAL, Bangalore) & her team worked on their main project objectives, which included (i)Analysis of model output of CFS hindcast runs (years: 1981 – 2008) for various variables (e.g., Surface temperature, Maximum temperature, Minimum temperature, Precipitable water, zonal and meridional components of wind and omega), using February and April initial conditions [provided by ESSO-IITM] and (ii) **Development of standalone boundary layer module**. Towards this development, they have identified the variables needed for the new boundary layer module. The derivation of these variables in the CFS code is also being analysed. Stand alone code, to find the new velocity scales, has been developed. This is being tested with actual observations. This code will be further modified to include the computation of the drag and heat flux coefficients. The stand alone module will be tested and verified by the end of second year. The future goal of this project is aimed at the Integration of the module into Monsoon mission model and Testing & Evaluation of the Module after integration.

❖ Contributions from International projects funded by Monsoon Mission:

- **Impacts of ocean-atmosphere coupling and SST high frequency variability on the coupled simulation of the mean state and variability of the Indian Summer Monsoon**

Prof. Terray Pascal (PI, LOCEAN-**IPSL**, University Pierre& Marie Curie, France) and his team had the project objectives related to (a) Role of **ocean-atmosphere** and **surface land-atmosphere** couplings in the coupled simulation of ISM at different time scales and the ISM biases, and (b) Importance of SST high-frequency variability and accurate ocean-atmosphere coupling in the simulation of ISM and Indian Ocean variability at different time scales. They have approached with a comparison of forced and coupled control simulations and several dedicated sensitivity coupled experiments conducted ***in parallel*** with two state-of-the-art CGCMs, the **CFSv2** (India) and **SINTEX-F2** (France) models. For this, Long control coupled experiments, large sets of nudged SST coupled experiments and sensitivity coupled experiments playing with the surface land albedo and roughness length have been performed with both the SINTEX and CFSv2 coupled models.The nudged SST coupled experiments demonstrate that correcting the SST biases in one tropical ocean basin (Indian, Atlantic and

Pacific) are beneficial for reducing the mean SST and rainfall biases in other oceanic basins. However, controlling these SST errors in the nudged coupled simulations are not sufficient to eliminate the rainfall biases over the core monsoon zones (India, Africa) during boreal summer in the coupled simulations(**Fig. 8**).These nudged SST experiments also demonstrate the strong impact of the Indian and Atlantic variability on ENSO and the realism of the monsoon-ENSO relationship as simulated in the CGCMs. A focus restricted to Indian region is not adequate!

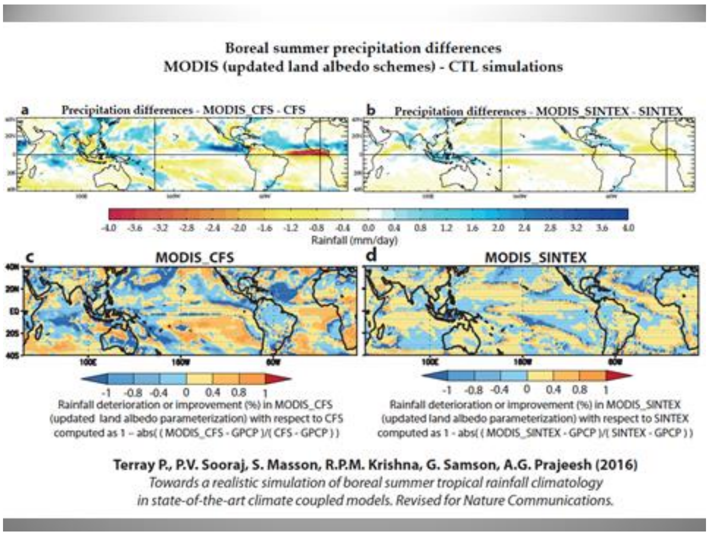


Fig. 8: Boreal summer precipitation difference (MODIS – CTL simulation)

The land coupled experiments demonstrate the significant role of the land surface biases (skin temperature, albedo, emissivity, roughness length) on the monsoon biases.These experiments have provided guidelines for revising the land surface albedo parameterization in both SINTEX and CFSv2 coupled models. The new schemes have reduced the land ISM rainfall errors and also tropical rainfall biases at the global scale in the two CGCM.

- **Ocean-Land-Atmosphere Coupling and Initialization Strategies to Improve CFSv2 and Monsoon Prediction**

Dr. James Kinter (PI from George Mason University& NCEP, USA) and his team had the objectives to (a) Improve forecasts of Indian summer monsoon rainfall (ISMR) in NCEP Climate Forecast System (CFSv2) using controlled experiments to rigorously explore (i) Refined initialization of the land surface; (ii) Multi-analysis ocean initialization& (iii) Improved representation of coupled processes; and (b) Improve understanding of influence on IMR predictability of (i) Long-lived sea surface temperature anomalies in the tropical oceans, (ii) Soil moisture anomalies in India and Eurasia& (iii) Complex land-atmosphere and ocean-atmosphere interaction.The NCEP CFSv2, adopted by MoES as ISMR prediction tool, ported to multiple HPC systems, exercised in long runs and reforecasts, and altered to evaluate impact on bias and predictability by various runs (e.g., 400-year simulation with modified CFSv2; 30 years of CFSv2 reforecasts from Jan., Feb., Mar., Apr., and May, using multiple ocean analyses; 30 years of CFSv2 reforecasts from Jan., Feb., Mar., Apr., May and

June, using large ensembles of perturbed land surface initial states). Modifications were made in CFSv2 code to correct a coding error in the ocean-atmosphere-sea ice interface, evaluate sensitivity to sea ice albedo, and implement heated condensation framework (HCF) for triggering atmospheric convection.They found a better ocean and land surface ICs and new ensemble techniques may be critical to improving seasonal predictability. ISMR is more predictable up to 2 seasons lead during the summer immediately after the peak of El Nino events.The atmospheric leg of feedback pathway may be too weak in CFSv2 in the monsoon region. The positive snow bias and the significant negative correlation between spring Eurasian snow cover and first 2 months of IMRhave important implications for sub-seasonal forecasts.There are systematic biases in CFSRR cloud cover. The HCF produces significant improvement in IMR variability on synoptic, intra-seasonal, and inter-annual time scales as well as better IMR onset forecasts. Land surface parameters from IMD website are valuable for model validation (Collaboration with Dr. Rajeevan, MoES, and Dr. Unnikrishnan, NCMRWF).

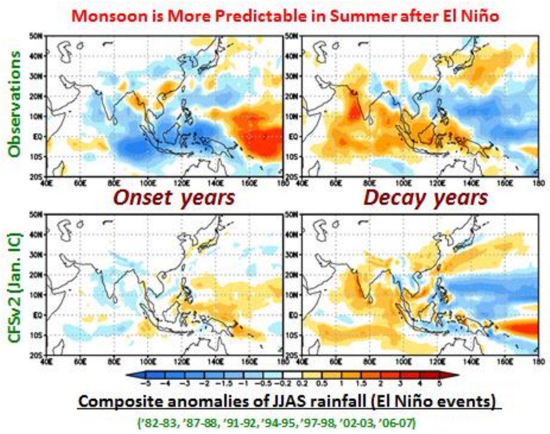


Fig. 9: Monsoon is more predictable in Summer after El-nino

- **Evaluation and Improvement of the Unified Model for Short- and Medium-Range Prediction of Monsoon Rain Systems**

Dr. Elizabath Ebert (PI from CAWCR, Bureau of Meteorology, Australia) and her team (including Dr. Kamal Puri) had worked on the objectives : (a) Model verification using advanced diagnostic methods, (b) Numerical experimentation and studies of selected rain events and (c) Evaluation of ensemble predictions; using Unified model and ACCESS model. They made first comparison of CRA and MODE spatial verification for monsoon heavy rain cases. Both methods characterise errors in rain location, amount, shape, etc. but have different detection and matching criteria. They found broadly similar conclusions about forecast quality. There were many similarities, like, CRA location error uses centre of gravity while MODE uses centroid difference; CRA provides error decomposition (location, volume, pattern); MODE gives more shape information. They have used both methods together to augment traditional scores to monitor model performance and diagnose areas for improvement. Higher resolution ACCESS-C provided more improvements. They worked on Tropical Cyclone (TC) Vortex Initialization scheme input from NCUM analysis of U, V, Temperature, Geop. Height and Relative Humidity at all pressure levels, and Surface Temp. , Surface Pressure and MSLP, in 4-steps: (a) Filtering of the analyzed circulation from the original analysis (b) Construction of an inner core of Cyclone, (c) Relocation of inner core to observed position and (d) Merging of relocated vortex with the large-scale analysis.

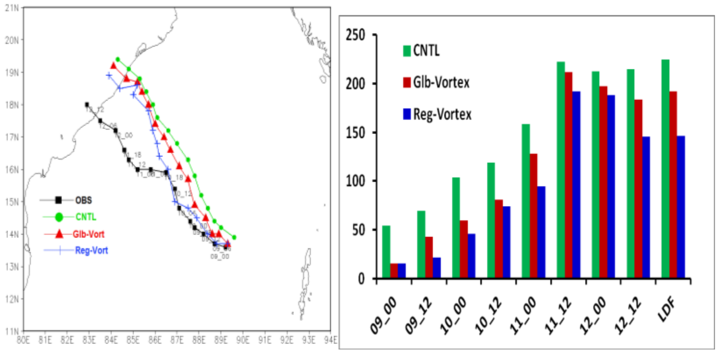


Fig. 10: Vortex Initialization with NCUM-G & NCUM-R based on IC: 20141009_00UTC (**TC Hudhud**)

- **Use of observations defining upper ocean processes in the Bay of Bengal towards improved weather/seasonal forecast.**

Dr. Ruby Krishnamurti (PI from FSU, USA) and her team have been working for improved weather/seasonal forecast and inter-annual variability of monsoon conditions, using observations related to upper ocean processes in the Bay of Bengal(and conditions during Bay of Bengal depressions). With the great progress resulting from recent research on the Bay of Bengal (BB) and the current physical modelling work at FSU, it is possible to improve the parameterization of upper ocean processes in the BoB for numerical forecast models. The primary goal of this project is to improve forecasts of seasonal and inter-annual variability of monsoon conditions and BB depressions by implementing such advanced parameterizations with Coupled Atmosphere-Ocean Models. Improvement in the parameterization of upper ocean processes, specifically for the Bay of Bengal basin, requires addressing the following areas in some detail : (a) Mixed layer depth and maintenance of barrier layers in the Bay of Bengal; (b) Salinity budget for the Bay of Bengal; and (c) Radiative processes in the mixed layer and the barrier layer; parameterization of turbidity in the Ganges-Brahmaputra riverine plume, and short wave radiative warming of the surface layer. They worked on two new experiments related to ways of removal of fresh rain and river water from their source regions : (a) The rate of fresh water transport by isolated lenses moving westwards on a beta plane, and (b) The rate of fresh water transport by isolated cyclonic lenses propelled counter-clockwise along a coast with their image lenses. (These are not coastal Kelvin waves which are gravity waves but actually isolated water masses). These results are needed for parameterization in coupled numerical prediction models.

➢ Understanding bias errors and addressing physics errors in the CFSv2 model to improve monsoon prediction

Dr. Brian Mapes (PI from University of Miami, USA) and his team had the hypothesis that Moisture sensitivity of convection is important to MISO/ISO, and too weak in models; Key parameter is entrainment rate of plume in deep convection scheme. But there is a dilemma: excess entrainment spoils the mean climate state(Mapes & Neale, 2011, JAMES). They had the plan to explore trick of RH-dependent entrainment (shown to improve ISV at ECMWF, Bechtold et. al., 2008, Hirons et al. 2013ab; and also implemented in GFS, Han and Pan 2011) and to optimize its parameters for India's monsoon.

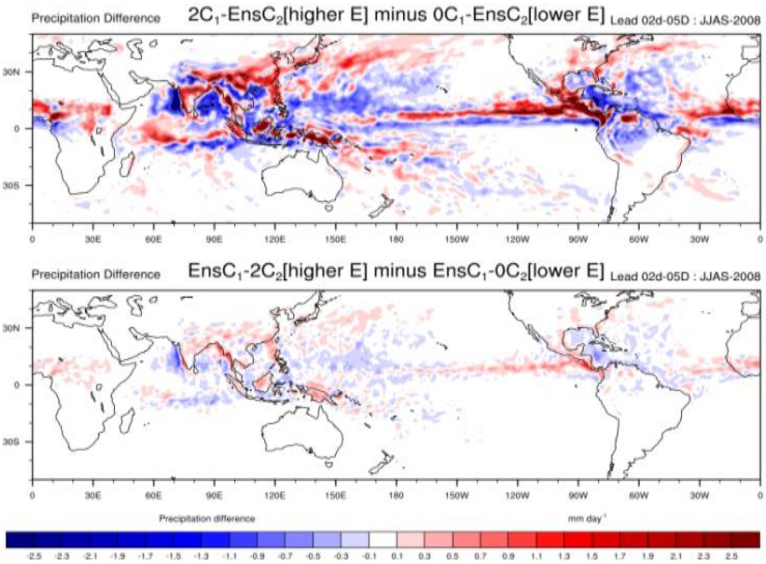


Fig. 11: JJAS Precipitation difference of ensembles for lead 2 to 5 days

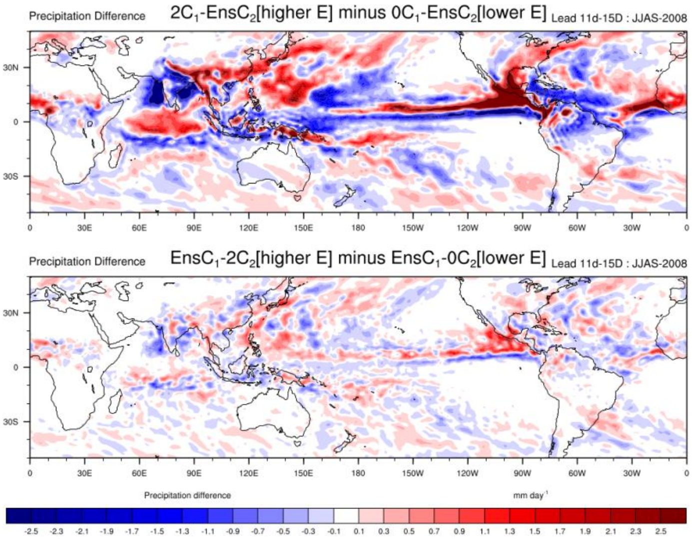


Fig. 12:JJAS Precipitation difference of ensembles for lead 11 to 15 days

The impact of increasing/decreasing entrainment has a one dimensional thermodynamic response of decreasing/increasing deep convection during the first days of forecast, and a complex dynamical response with increasing forecast lead-time (as in Bush et al. 2015 QJRMS). The impact of RH-dependent term (cxlamu) part is very weak in its current implementation in GFS. For instance, ECMWF has gone to a 7x larger coefficient, while we only triedthe range [0,2]. As a result, S/N ratio only allowed us to detect its effect in very highly averaged time-mean ways (figures above), not in satisfyingly lead-dependent skill metrics. Need to try a much larger range for C2.

- **Stochastic Parameterization and Forecasting of Wind Energy in India**

Dr. Ralf Toumi (PI, Imperial College, London, UK) and his team worked on Stochastic Parameterization scheme in Unified model (in association with NCMRWF) and utilized it for Forecasting of Wind Energy in India.

- **Improving Monsoon Predictions with a Couple Ensemble Kalman Filter Data Assimilation System**

Prof. Eugenia Kalnay (PI, University of **Maryland**, USA) and her team worked on the following :(a) Development of a strongly coupled data assimilation for the CFS v2 for the use of IITM to make seasonal forecasts more accurate than the current ones. (b) Estimating and correcting the model systematic errors in the GFS (and later in the CFS).

They proposed to **develop a "strongly coupled" data assimilation method** for the CFS coupled model, unlike the present coupled assimilations, done separately for the ocean and the atmosphere, followed by coupling of the models. In this standard method, called "weakly coupled data assimilation" the atmosphere only assimilates atmospheric observations and the ocean only assimilates ocean observations. They took advantage of the Local Ensemble Transform Kalman Filter (LETKF) to allow for the ocean to assimilate the atmospheric observations, and the atmosphere to assimilate ocean observations.

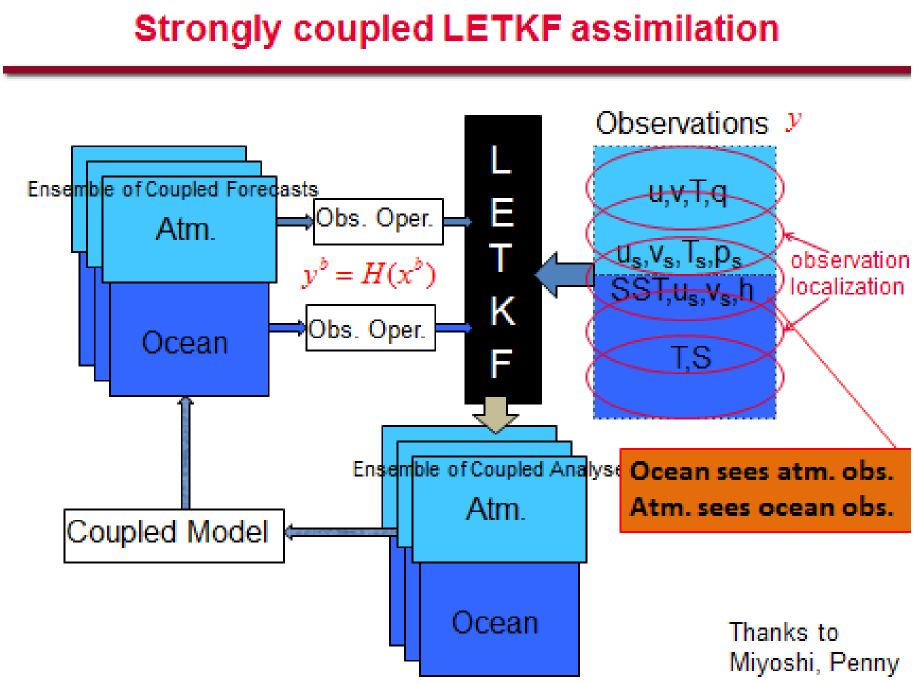


Fig. 13: Schematic figure forStrongly coupled LETKF assimilation

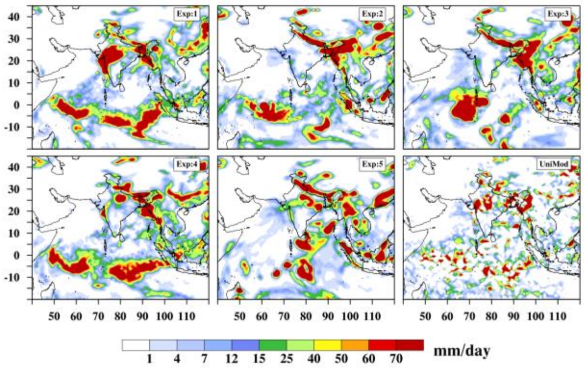
Sluka et al (2016, GRL) tested the methodology with the SPEEDY GCM coupled with the NEMO ocean model, with excellent results indicating that the Strong Coupling resulted in major reduction of errors when compared with the Weak Coupling. In turn the atmosphere also improved because the coupled ocean errors decreased.The project PDF Travis Sluka then developed the Weakly and Strongly coupled data assimilation with the LETKF using the operational CFS model and real observations. The first experiments were carried out for JJA2005, with the atmosphere assimilating all atmospheric observations (except radiances), and including surface ship temperature and moisture., and the ocean just coupled to the atmosphere in the Weakly Coupled case. In the strongly coupled case. Same as the weakly coupled,but with the ocean also assimilating surface ship observations, the results are also encouraging, indicating that the ocean warm bias in the NH summer, especially near the continental coasts, is reduced due to the assimilation of surface ships. In turn, the atmosphere bias is also reduced by the strongly coupled assimilation due to the less biased coupled ocean.The weakly coupled version of the LETKF-CFS was provided to ESSO-IITM (during visit of Dr. Sreenivas Pentakota to University of Maryland, USA).

For **Estimating and correcting the model systematic errors** in the GFS (and later in the CFS), project student Kriti Bhargava has worked with PI Kalnay and Co-PI Jim Carton estimating the model 6hr bias as the time average Analysis-6hr Forecast = Analysis Increment (AI). This is because the AI is the correction made to the 6hr forecast based on the new observations, and estimates the bias before the model errors grow nonlinearly. Following Danforth et. al. (2007), Danforth and Kalnay (2008), they plan to correct the model “online” by adding to each variable time derivative at each grid point the AI divided by 6hr. They found that the average AI are very robust (see Fig. 6),very similar in 2012, 2013 and 2014. They also found that they could represent the diurnal errors with just 4 EOFs of the full diurnal errors. These results are quite promising, since Danforth and Kalnay (2008) found that this not only reduced the model systematic errors as the standard a posteriori systematic error correction, but, because the model was improved by the error correction, the random errors were also smaller. These results suggest that the average AI/6hr can be added to all the variables and all the levels, and correct much of the systematic errors, as well as the diurnal cycle errors. In addition they greatly facilitate the testing of new physical parameterizations, which should reduce the analysis increments.

Thus, the project has made important and encouraging achievements, clearly showing for the first time that, Strongly coupled Ocean-Atmosphere Data Assimilation is more accurate than the standard Weakly coupled DA, in which the ocean only sees oceanic observations, and the atmosphere only atmospheric observations, and the two systems are just couple by their models. Results were shown for a perfect model OSSE, and for the NCEP CFS assimilating .

- **Sensitivity Studies for Indian Summer Monsoon Forecast Modelling**

Prof. T. N. Krishnamurti (PI, Florida State University, USA) and his team carried out Sensitivity Studies in CFSv2 model. The main objective of this project is to improve the forecasting capabilities of Monsoon Mission Model in order to provide reliable forecast for different applications. One of the most important jobs was the removal of Dry Bias in the CFS Model using a unified model of CFS multi-physics runs. In this study, they proposed to develop a suite of CFS models with same dynamical core but different physical parameterizations including the microphysics schemes. These models are used to carry out a large number of hindcast simulations with same initial and boundary conditions. Thereafter, rationale of Krishnamurti and Sanjay (2003) is applied to construct a new unified CFS model with an aim to reduce the dry bias of original CFS model, by constructing a multi-model super-ensemble from the results of the suite of above models. The super-ensemble is based on the skill of performance of forecasts of the moisture and precipitation fields of each member model. It was first verified that the multi-model super-ensemble, based on the above suite of models, reduces the dry bias of single individual models. That reduction of bias is related to the persistent systematic errors (drying) that each member model carries. TheSuper-ensemble is designed to reduce the collective bias errors. In the process of preparing the super-ensemble forecasts statistical weights describe the characteristic of each model. Those weights vary in space (three dimensional grid array), time and model (each is tagged). This ends up becoming close to a million statistical weights that provide corrections for the collective bias errors. Using those weights within the above single CFS model (that carries all of the above physics / microphysics strung out within a single model), we construct a unified CFS model. This new unified CFS model and the forecast (that now uses an independent set of initial conditions) with this model will be more reliable for short term forecast based applications.



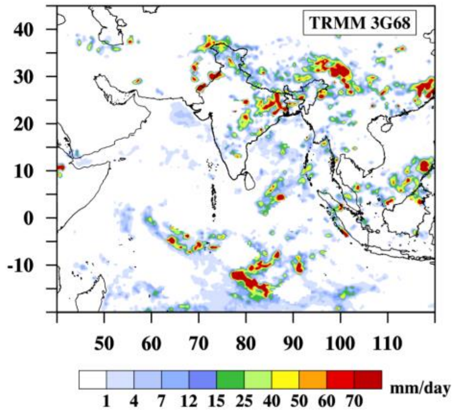


Fig.14: Unified model: Day-15 Forecast: 15 Jul 2012**Fig.15** :Observation TRMM TMI (3G68): 15 Jul 2012

- **A novel approach for improving rain-gauge data assimilation and extended-range prediction of sub-seasonal variability over India**

Dr. Ajaya Mohan Ravindran (PI from NYU, Abu Dhabi, UAE) and his team worked on the following project objectives (a) To develop a new extended-range monsoon forecasting technique based on NLSA and SPEKF-type models using observations and coupled model outputs, and assess its skill, and (b) To develop a state-of-art methodology for assimilating a large-scale network of rain gauge data spanning the Indian subcontinent.As an important outcome, an improved index for the real-time monitoring and forecast verification of MISO is developed using Nonlinear Laplacian Spectral Analysis (NLSA) algorithms, which has the potential to capture the low-frequency variability and intermittency. Using NLSA, a hierarchy of Lapalce-Beltrami (LB) eigen-functions are extracted from unfiltered GPCP rainfall data over the Asian monsoon region.

Two modes representing the full life cycle of the northward propagating MISO are identified from LB eigen functions (Modes 5 and 6) and it shows strong seasonality with high amplitude during boreal summer months and weak amplitude during other seasons. These two modes have number advantages over MISO modes extracted via conventional method (for example EEOF), including higher memory and predictability, stronger amplitude and higher fractional variance over the western Pacific, western Ghats and adjoining Arabian Sea regions and therefore more realistic in representing the regional heat sources over Indian and Pacific oceans.

The skill of the NLSA-based indices in real-time prediction of MISO is demonstrated in extended-range hindcast (45-day run) of the NCEP CFSv2 model. It is shown that these indices yield a significantly higher prediction skill than conventional indices (EEOF) supporting the use of NLSA in real-time prediction of MISO.

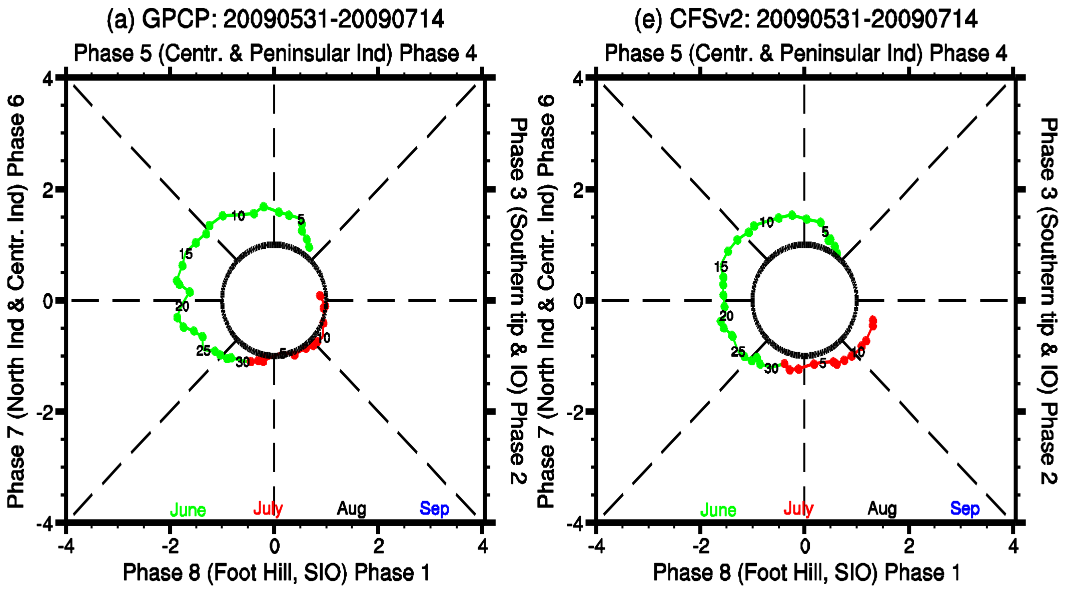


Fig.16: An example of MISO evolution: Forecast of NLSA MISO indices for 2009 May 31 initial condition runs of CFSv2 (Right panel) is verified against GPCP rainfall data (Left panel). [Ref: Sabeerali C. T. , R. S. Ajayamohan, D. Giannakis and Andrew J Majda, (2016) Extraction and prediction of monsoon intra-seasonal oscillations: An approach based on nonlinear Lapalcian spectral analysis. *Climate Dynamics* (under review)]

- **Improved Indo - UK capability for seamless forecasting of monsoon rainfall: from days to the season**

Dr. Andrew Turner (PI, University of Reading, UK) and his team worked on projective objectives to (a) Improve the simulation of the mean monsoon and its variability on daily to weekly time scales, with added benefits at seasonal and climate scales, by understanding, testing and improving the impact of convective parameterizations and (b) Improve monsoon prediction in the Unified Model on time scales of several days through weeks, with added benefits at seasonal and climate scales, by testing the sensitivity of forecasts and hindcasts of summer monsoon rainfall to mean state SST and surface wind biases in the equatorial Indian and Pacific Oceans and developing techniques to correct biases in the operational forecasting framework. They found potential improvements in Indian monsoon precipitation by increasing entrainment parameter.

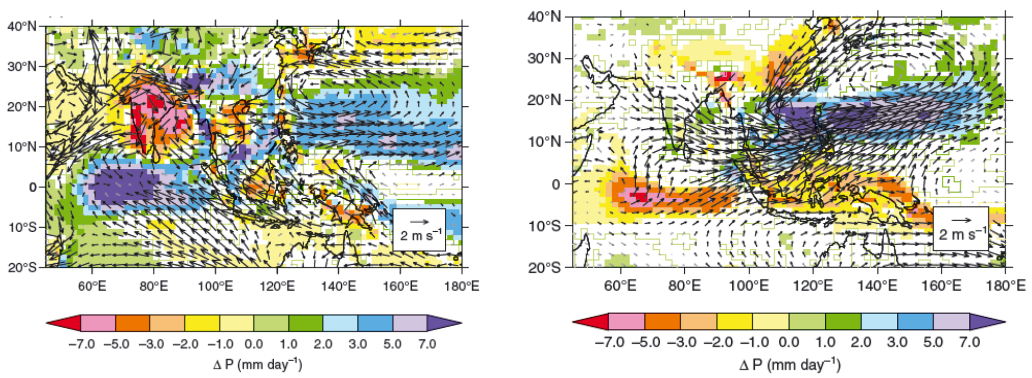


Fig.17 : The effect of increased convective entrainment on Asian monsoon biases in the MetUM General Circulation Model. (Ref :Bush, S. J., A. G. Turner, S. J. Woolnough, Gill M. Martin and N. P. Klingaman)

They detected Large dry biases in a version of the MetUM (left), consistent with CMIP5 models.Rainfall can be increased over India (right) by adjusting the entrainment rate parameter in the convection scheme, but biases worsen elsewhere, e.g. WNP. Increased resolution (from N96 to N512) improves representation of the Somali jet in the vicinity of the East African Highlands, strengthening the monsoon circulation; only minor improvements are made to Indian rain. They showed competitive performance of monsoon seasonal prediction in Met Office GloSea5 model. Equatorial Indian Ocean shown not to support adequate air-sea interactions in GloSea5. They wish to test role of May soil moisture initialisation over India on subsequent development of monsoon biases and to investigate role of coupled biases in Indian Ocean using Met Office coupled thermodynamic ocean mixed layer model MetUM-GOML to test relaxation to observed and GloSea5 model climatology.

- **Advancing Monsoon Weather-Climate Fidelity in the NCEP CFS through Improved Cloud-Radiation-Dynamical Representation**

Dr. Dune Waliser (PI from University of California, USA) and his team performed rigorous observation-based evaluation and diagnostic analysis on contemporary weather/climate models with the aim at understanding and improving model representations of monsoon mean & intra-seasonal variability (ISV), with a particular focus on cloud/convection-radiation-dynamic interactions, microphysics, vertical structure, and the use of satellite observations.

They examined (a) Contemporary multi-model prediction skill & predictability study of Boreal Summer Intra-seasonal Oscillation (BSISO), and (b) Contemporary multi-model performance metric and process diagnostic study for the BSISO. They Characterized observed vertical profiles of cloud ice/liquid water and SW & LW radiation for the BSISO. Global detection algorithm for atmospheric rivers (ARs) has been developed, showing AR relevance to S. Asian monsoon region. Atmospheric rivers (ARs), narrow corridors of enhanced water vapor transport, are major precipitation deliverer, drought breaker, and flood producer in many parts of the world. The global distribution of ARs, especially those outside of the extra-tropical continents, remain poorly characterized and understood, with a notable obstacle being the lack of AR identification algorithms suitable for global studies. A new technique is developed for objective detection of ARs based on characteristics of the vertically integrated water vapor transport, with novel and important considerations made to enable application on the global domain.

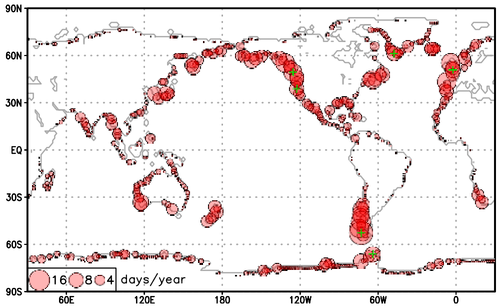


Fig.18 : The average number of days per year with atmospheric river (AR) landfalls during 1997–2014. AR landfalls are most frequent along the west coasts of North America, southern South America, and Europe, but also notable in other areas, including South/East Asia.

Examination of key AR characteristics over the period of 1997–2014 highlights the global footprints of ARs. El Niño/La Niña and three other prominent "modes" of large-scale climate conditions are found to significantly modulate AR activities in various regions of the world, implicating potential long-term predictability of AR activities in these regions.

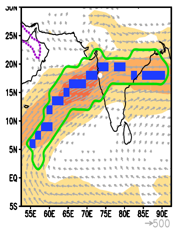


Fig. 19: Example of an AR making landfall in India on June 21, 1997. Shown are the AR shape boundary (green), axis (blue), landfall location (white dot), and the integrated water vapor transport (gray arrows).

The study represents an important step forward in characterizing and understanding AR activities on the global scale. Notable footprints of ARs in South/East Asia have implications to possible connections between ARs and monsoons. The AR catalog generated from this study, which includes the AR shape, axis, landfall location, and basic statistics of each detected AR, provides the community a long-awaited AR dataset suitable for global observation and model evaluation studies. Also, their model sensitivity study showed importance of radiative effects of snow on tropical radiative heating profiles.

- **An approach of Multi-scale multi-cloud parameterization to improve the CFS model fidelity of monsoon weather & climate through better organized tropical convection**

Dr. Bouleam Khouider (PI from University of **Victoria**, Canada) and his team worked on their project objectives to (a) Implement and test a new stochastic multi-cloud (SMCM) parameterization approach in CFSv2 to improve prediction skills of monsoon weather and climate. SMCM is based on theory and observations of tropical multi scale convective systems. SMCM acts as a cheap alternative to cloud-resolving parameterization, in the sense that it aims for an accurate representation of sub-grid variability due to mesoscale convective systems as a building block (b) To successfully implement SMCM in CFSv2 environment major training and tuning of the method where required in order to bring the theory into practice.They have successfully calibrated SMCM using reanalysis and large-eddy simulation data, and tested in an aqua-planet GCM and simple zonal symmetric monsoon model. Then, they successfully implemented SMCM in CFSv2 using parameters values and model configuration learned in earlier exercise. Preliminary simulations with CFS-SMCM reveal major improvements in CFS capability in representing synoptic and intra-seasonal in tropics and Indian monsoon region.

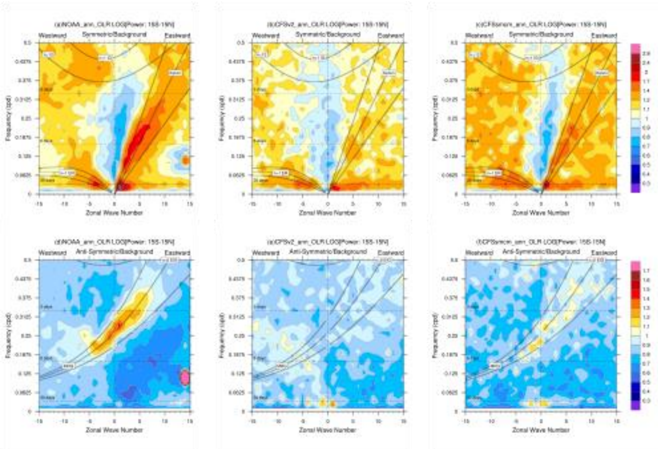


Fig. 20: Spectral peaks of tropical rainfall in observations (right), CFC-SMCM (left), and CFSv2 (middle). A clear improvement in capacity of SMCM to realistically capture both intra-seasonal and synoptic scale waves is evident.

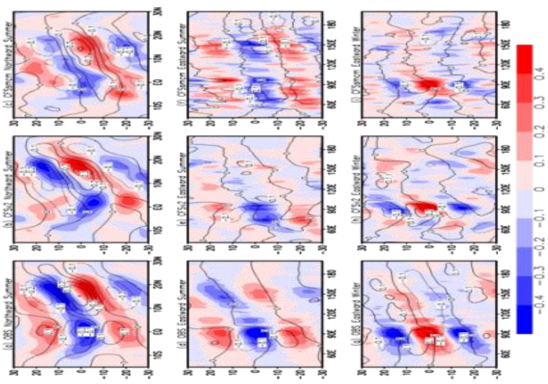


Fig.21 : Improvements in terms of Northward and Eastward Propagation of convection. SCM has a better (faster) northward propagation and eastward propagation beyond maritime continent barrier (especially during monsoon season)

- **Understanding the role of sea surface temperatures in the simulation and prediction of the monsoon intra-seasonal oscillation**

Dr. Arun Kumar (PI from University of **Maryland,** USA and Climate Prediction Center, NCEP/NWS/NOAA, USA) and his team (including Prof. Raghu Murtugudde of University of **Maryland,** USA) assessed CFSv2 predictions of MISO, and analyzed the impact of the SST on the prediction of MISO. They worked to improve SST intra-seasonal and diurnal variability in the ocean model, and to investigate impacts on the atmospheric intra-seasonal variability of the SST representation of SST in coupled models. They found that MISO is less predictable than MJO (ACC=0.5 at day 13 for MISO and at day 20 for MJO. Beyond 2 weeks, MISO is most predictable when initialized **from *phase 1***and **from *phase 5*** and least predictable **from *phase 3.***Predictable length in CFSv2 is shorter than the estimated potential predictability (~30 days) of MISO and MJO, suggesting possible rooms of further improvements. They made an Analysis of SST impacts on MISO and MJO simulations with uncoupled GFS.

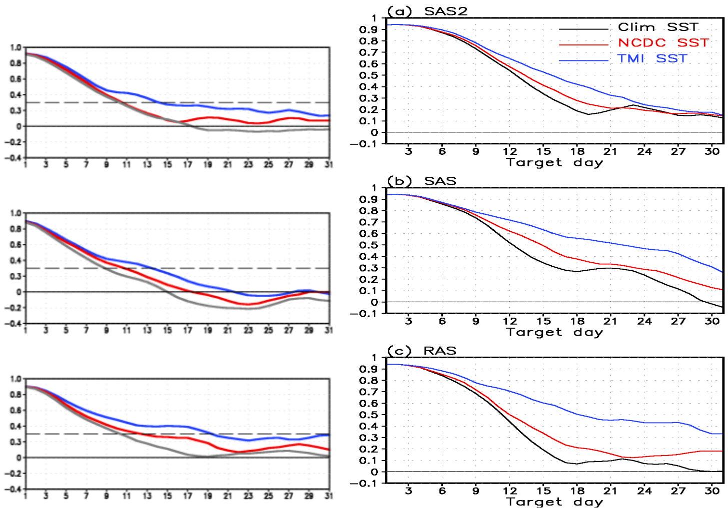


Fig.22 : Both MISO and MJO simulations strongly depends on the specified SSTs. Specifications of the TMI SST retrieval results in better simulations than the NCDC SST analysis.The dependence of the simulation skill on the SST is consistent across different convection schemes.

They used 3 types of Convection schemes :SAS (Simplified Arakawa-Schubert Scheme), SAS2 (Simplified Arakawa-Schubert Scheme 2) and RAS (Relaxed Arakawa-Schubert Scheme). SSTs were obtained from TMI (TRMM Microwave Imager), NCDC (National Climate Data Center) and NCDC 1998-2014 Climatology (Clim).

They also obtained Improvement of simulated SST variability with higher ocean vertical resolution, using MOM5 Model with 1M (Simulation with 1 m vertical resolution) and 10M (Simulation with 10 m vertical resolution). 1M simulation realistically captured the observed ocean temperature diurnal cycle. SST diurnal range in 1M is 0.2 to 0.3 larger than that in 10M. Daily SST STDV in 1M is 0.05-0.1K stronger than in 10M, comparable to SST STDV differences between TMI and NCDC SSTs, suggesting the possibility to improve MISO/MJO simulation with 1 m vertical resolution.

- **Role of the Atmosphere and the Indian Ocean in the Evolution of Monsoon-ENSO Tele-connections in CFS**

Prof. Raghu Murtugudde (PI from University of Maryland, USA) and his team had the project Objectives to (a) Analyze the summer monsoon biases stemming from Indian Ocean air-sea interactions and the overlaying atmosphere biases, (b) Analyze and understand the evolution of the Indian Ocean SST biases and their relation with summer Monsoon, (c) Explore the telecommunication mechanisms between Bay of Bengal and Indian Ocean in terms of the organized convection, (d) Study the role of MISOs and active and break events on the summer monsoonal biases, (e) Understand the ENSO-Monsoon-IODZM evolution in the context of CFS monsoon biases, (f) Understand and analyze biases in ocean and atmosphere components individually through AMIP and coupled runs and (g) Explain ocean biases stemming from mixed layer diurnal cycle and freshwater forcing. They made adetailed study on ocean-atmosphere coupled bias evolution which leads to dry summer monsoonal bias in CFSv2 seasonal forecasts.

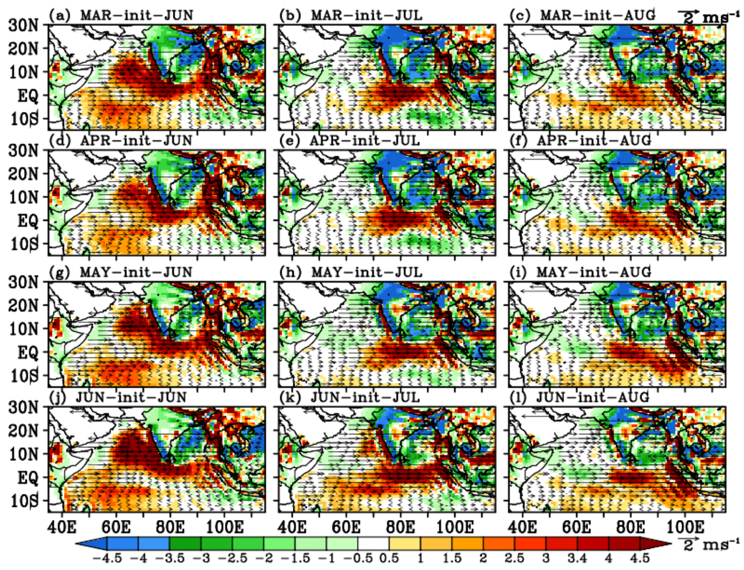


Fig. 23: Biases in precipitation (color shades in mm day-1) and 10-m zonal-wind component (forecasts-observations) during June, July and August, initialized in March as depicted in (a), (b), and (c), initialized in April as depicted in (d), (e), and (f), initialized in May as depicted in (g), (h) and (i), and initialized in June as depicted in (j), (k), and (l), respectively.

Their study led to the following methodology for bias propagation.

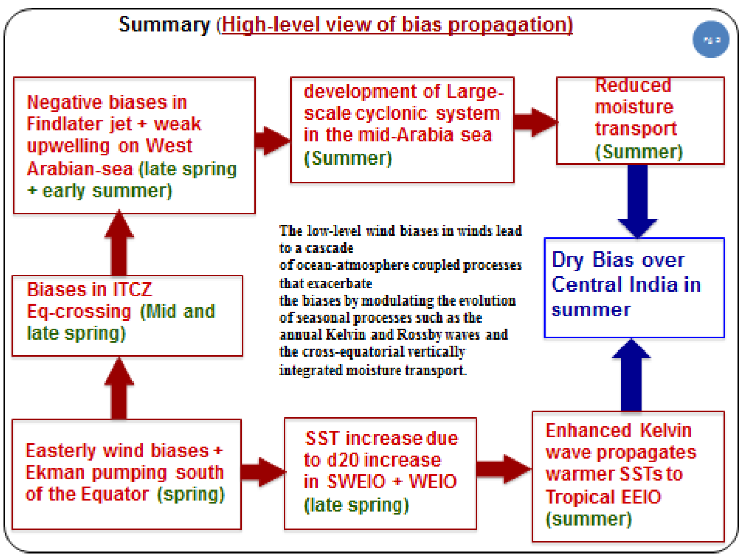


Fig. 24: High level view of bias propagation

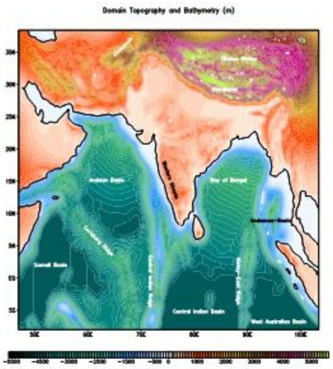
- **Extended Monsoon Episodes: Understanding Processes and Pathways for Improved Prediction in CFSv2**

Dr. H. Annamalai (PI from University of Hawaii, USA) had 3 important project objectives (a) To identify and quantify the processes that initiate, maintain and terminate extended monsoon episodes in multiple global reanalysis data sets and then use field observation to constrain uncertainties in the reanalysis products, (b) To examine if these processes are faithfully represented in the free runs and hindcasts performed with CFSv2, and if not, to offer recommendations for model improvements, and (c) Based on the identified physical processes, to incorporate nudging on model equations in CFSv2 and perform a series of prediction experiments and assess their skill. First two objectives (a & b) have been completed through Process-based diagnostics applied on a suite of reanalysis and CFSv2 simulations/hindcasts. Robust processes that govern the life-cycle of monsoon extended episodes over central India are identified, and their relative roles were "quantified". Robust results obtained here recommend monitoring of "key processes" to predict the onset, intensity and duration of extended monsoon episodes over central India. As regards to CFSv2 model processes, they identified (a) lack of precipitation sensitivity to free troposphere moisture variations, and a too weak cloud-radiation feedback, and (b) large-systematic errors in mixed-layer parameterization leading to SST errors over the tropical Indian Ocean.

They are working now working on the third objective, i.e., they are planning Process-nudging experiments with CFSv2.Further process-based diagnostics are applied to CFSv2 hindcasts (initial conditions ranging from May to July) – with a particular focus on events such as the July 2002.

- **Regionally coupled ocean-Atmosphere seasonal hindcasts of the Indian summer monsoon at 10 Km resolution**

Dr. Vasubandhu Misra (PI from Florida State University, USA) and his team worked on the project objectives to (a) Conduct comprehensive diagnostics of deterministic and probabilistic skill analysis of the regionally coupled seasonal hindcasts and compare them with the corresponding CFSv.2 hindcasts, (b) Understand and diagnose the high frequency air-sea interaction at and before the time of Indian summer monsoon onset, during the summer monsoon and at and after the demise of the monsoon, (c) Examine the intra-seasonal forecast skill from the regionally coupled ocean-atmosphere model with standard metrics for the boreal summer monsoon, and (d) Conduct detailed analysis of weather and climate extremes in the downscaled hindcasts. They have successfully downscaled one CFSv2 hindcast provided by IITM-Pune with the regional coupled model over India and its results were submitted as part of the first year annual report. They have also successfully downscaled 22 years from global atmospheric and oceanic reanalysis over India to test the fidelity of the Indian monsoon simulation from the regional model. They are examining the impact of air-sea interaction and cloud radiative feedback separately from the regional model integrations of the Indian monsoon simulation. They will transfer the code to ESSO-IITM to work at its HPC Aaditya.



Domain and resolution of topography and bathymetry resolved by the regional coupled ocean-atmosphere model

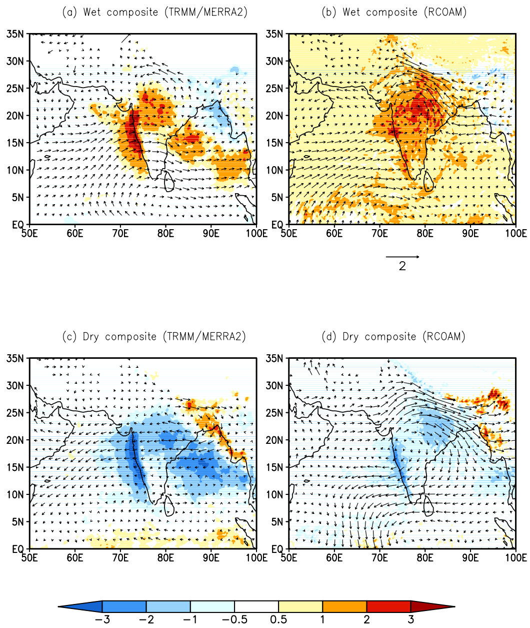


Fig. 25: Composite band pass filtered (20-90 days) 850hPa winds overlaid with precipitation anomalies for wet spell from a) TRMM3B42 (rainfall) and MERRA2 (850hPa winds) and b) Regional Coupled simulation of 23 years forced by atmospheric NCEP-R2 and SODAv2 ocean reanalysis.

- **Indian Ocean air-sea interaction Processes and their Effects on Indian Summer Monsoon Intra-seasonal Variability: with implication for improving CFS2 monsoon forecast**

Prof. Weiqing Han (PI from University of **Colorado** at Boulder, USA) and her team used the NCEP/CFSv2, together with in situ and satellite observations combined with standalone

OGCM experiments, to advance our understanding of the Indian Ocean air-sea interaction processes associated with the Indian summer MISOs, and to provide insight into the role played by Indian-Ocean air-sea coupling in affecting Indian monsoon active and dry spells, with an ultimate goal of improving CFSv2 monsoon prediction skill. They found MISOs are strongest during May-June ISM (Indian summer monsoon) initiation stage comparing to mature and decay stages (over Eastern Arabian sea); this feature is not present in the Bay of Bengal. CFSRv2 produced general MISO features in EAS, but has quantitative biases in SSTa & Precipitation.

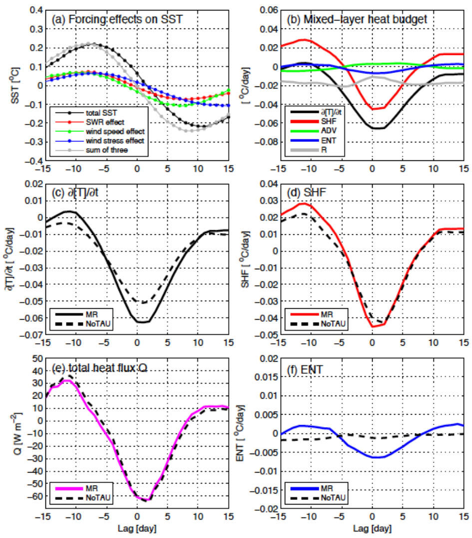


Fig. 26: (a) 20-90 day SST of the composite MISO averaged over the EAS from HYCOM Main Run (MR; black) and those produced by SWR effect (red; ~Qsw/mld), wind speed effect (green; (Qsen+Qlat)/mld due to wind speed change, wind stress effect (blue; measuring entrainment, upwelling & horizontal advection), and the sum of the three effects (grey); (b) Mixed-layer heat budget of the composite MISO for the EAS: mixed-layer temperature tendency ∂[T]/∂t (black solid), surface heat flux forcing term SHF (red) that is ~Qnet/mld, horizontal advection term ADV (green), vertical entrainment term ENT (blue), and the residual term R (grey) computed from MR output; (c) ∂[T]/∂t, (d) SHF~Qnet/mld, (e) total heat flux Q (W/m2), and (f) ENT terms computed from MR output (solid) and NoTAU output (black dashed).

Effects of Qsw, (Qsen+Qlat) due to wind-speed change, and wind stress driven (entrainment+dynamics) are comparable- see (a); Budget analyses shown in panels (b)-(f) demonstrate that wind-stress induces MLD change, which alters ~SHF/MLD - resulting in dominant of SHF/MLD; The thin MLD in May-June (green & purple lines in Fig. below) amplifies SSTa; the high mean SST (~30C) amplifies MISO, Precip response to SSTa, resulting in the strongest MISOs in ISM developing stage.Comparing to the thin MLD&BLT case, the thick MLD&BLT case appears to "sustain" convection and "prolong" its period, likely due to the high heat content sustaining a "weak but persistent warm SSTa". All of these results demonstrate that the **Indian Ocean processes play an important role in MISO mechanisms**.

- **Indian Monsoon Data Assimilation and Analysis**

Dr. Richard Renshaw (PI from Met Office, U.K.; earlier PI :Prof. Dale Barkar of UKMO) and his team worked for Data Assimilation and Analysis over Indian monsoon region. They were involved in Regional SURF (EKF) for soil moisture analysis- using screen-level observed T/RH to update soil moisture; Regional VarBC for satellite radiance bias correction - biases updated every cycle within the assimilation; TOVS satellite radiance assimilation-capability to assimilate TOVS radiances (1979-2004). They developed Capability to read conventional obs from early period (surface, sonde, aircraft) from ECMWF BUFR archive and Capability to produce verification (VER system) from ECMWF BUFR obs. They made Reanalysis UM systems functional at NCMRWF (UM, SURF, OPS, VAR, VER).

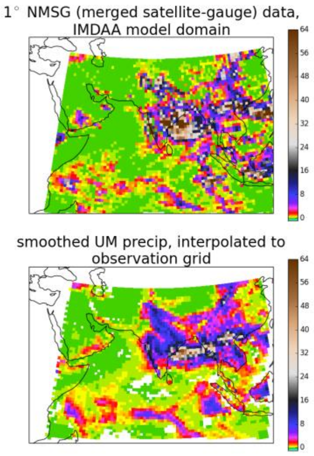


Fig. 27: Precipitation data to be assimilated is gridded rainfall data (TRMM/GPM + Gauge) prepared by Mitra et. al. (Mitra, A. K., A. K. Bohra, M. N. Rajeevan and T. N. Krishnamurti, 2009, Daily Indian precipitation analyses formed from a merged of rain-gauge with TRMMTMPA satellite derived rainfall estimates, J. of Met. Soc. of Japan, 87A, 265-279.)It is available at different resolutions for three periods: (a) 1998 to May 2012 , 1 x 1 deg (b)June 2012 to Sep 2015, 0.5 x 0.5 deg and (c) From October 2015, it is merged GPM gauge data at 0.25 lat/lon grid.

24-hour accumulations need to be disaggregated to 6-hour periods for assimilation. They havesplit the observed 24-hour accumulation into 4 in the same proportions as found from a 24-hour UM forecast for a nearby gridpoint. Horizontal smoothing is applied first to the UM forecast as this increases the likelihood there is a nearby UM grid point with similar precipitation.

- **Improving multi-scale variability and inter-actions in a global coupled seasonal climate forecast system through embedded regional modelling at weather and cloud resolving scales**

Dr. Saji N. Hameed (PI from University of Aizu, Japan) and his team is working on the project to improve multi-scale variability and inter-actions in a global coupled seasonal climate forecast system through embedded regional modelling at weather and cloud resolving scales.

- **Improved under-standing and representation of land surface processes for short, medium and long range prediction of monsoon rainfall"**

Prof. Dev Niyogi (Purdue University, USA) and his team is working on representation of land surface processes for short, medium and long range prediction of monsoon rainfall using dynamic model for better understanding of land surface processes and their representation in the model.

Achievements against the proposed objectives:

Working partnership has been established between the Academic and R⎫ & D Organizations, both national and international and the MoES to improve the monsoon forecast skill over the country. MoES organizations share the responsibility of making seasonal and extended range predictions as follows INCOIS◊ NCMRWF ; Ocean ◊Preparation of Initial Conditions : Atmosphere ◊ IITM; Short range ◊Prediction/Hindcast runs: Seasonal and Extended range IMD/IITM/NCMRWF Partnership with other organizations NCEP/IITM/GMU/Univ. of◊Model developmental activity on CFS/GFS Victoria/FSU/IPSL /Purdue Univ./NAL UKMO/NCMRWF/BoM/◊UM IITM/INCOIS/Univ. of Maryland◊Data Assimilation research/development CFS based UKMO/BoM/Allahabad◊UKMO based Univ./Met. Office Model diagnostics/biases: IITM/IISc./A.U/CUSAT/C.U/Allahabad/TERI/Univ. Maryland /NYU/FSU/Univ. Aizu/Univ. Miami/Univ. Reading/UCLA/IPRC/Univ. Colarado Observational support: IISc./IITM/INCOIS/IMD/NCMRWF Dynamical modeling framework for improving the prediction skill of seasonal and⎫ extended range predictions was also successfully accomplished. Initially, IITM was given the responsibility to setup dynamical seasonal and extended range prediction system and recently the responsibility to setup ensemble prediction system for making short range forecasts was also bestowed on IITM. The main responsibility of the IITM was to use CFS model of NCEP as base model for setting up the above systems and to make developments on the base model. Very high resolution (T382L64 ~38 km horizontal resolution) dynamical seasonal⎫ prediction system was setup with improved (~ 20%) prediction skill of monsoon over India. Other leading centers run their seasonal prediction system at TL255 (~ 77 km; ECMWF), N216 (~ 50 km; UKMO) and T126 (~110 km; NCEP). CFS based Grand multi model ensemble prediction system has been setup to predict the⎫ active/break cycles of monsoon with reliable prediction skill up to 3 pentads and skillful guidance up to 4 pentads over the country. IITM has setup high resolution T574 (Semi-lagrangisn core) Global Ensemble Forecast⎫ System (GEFS) for short range forecast with 21 ensemble member. This system is being used to provide real-time short range emsemble forecast since June 2016. This forecast has been extensively use by IMD forecast offices at New Delhi and other centers during 2016 Monsoon months. A very high resolution T1534 (~11 km) deterministic forecast system has also been set up since August 2016 for short range predictions using GFS. Efforts are presently underway to setup ensemble prediction system based on GEFS at T1534 (~11 km) resolution as a commitment to Niti-Ayog Model developmental activities (convective parameterization, cloud microphysics schemes, Land Surface processes, ocean model, super parameterization etc.) to reduce the model biases and thereby probable improvement in prediction skill has been successfully undertaken with in-house developmental activities. Initial version of Indian model based on these developments has been implemented to test the improvements in seasonal prediction skill. Integration of model developmental activities in to the above model carried out by other collaborating institutes will be initiated shortly. Documented ocean/atmosphere model biases and diagnosed potential direction for improvements. Coupled data assimilation system based on CFS-LETKF has been setup at IITM. The system at present is weakly coupled system. Out of 70 research papers published on CFS model diagnostics and developmental activities in last 5 years more than 70% of these papers were published by IITM. Capacity building: A significant number of early career scientists have been trained in model development and data assimilation through the MM efforts, initially via the Monsoon Desk and later through interaction in the collaborative projects building for the first time a critical mass of model developers in the country. Technical: Monsoon Mission emphasized the need for high-end HPC not only for improved weather prediction, seasonal prediction and climate change projections but also for R & D to improve the existing skill of the models for all these set of predictions. By procuring and installing the two high-end HPC (800 TF at IITM and 350 TF at NCMRWF) under the MM, IITM demonstrated that indeed adequate computational infrastructure is an essential necessary condition for improved forecasts. IITM was also given the responsibility to manage the larger system and provide the computational facilities to all computations of IMD and INCOIS. By managing the computation needs of not only of IITM but also for IMD and INCOIS well in the HPC, IITM has shown maturity in managing such large HPC system in the country. We believe this is also a spinoff achievement. Majority of these achievements have been documented in high impact journals and some technical reports (list of Publications relevant to the project are attached as Annexure I)

- **CONCLUSIONS:**

Indian summer monsoon is the lifeline of India, providing about 80% annual rainfall in a short span of four months from June to September and providing the necessary boost to the economy of the country. Thus, monsoon forecast is an indispensable need of the country for efficient management of agriculture, hydrology, power sector, disasters, etc. The forecasts should have sufficient skill, so that it can be believed by the users. Statistical models had limited ability to predict weather/climate extremes, hence there was a need for a coupled dynamical forecast system which can model the ocean-atmosphere-land interactions through a set of mathematical equations. Monsoon Mission has taken the responsibility for improving the skill of monsoon weather/climate forecasts using coupled dynamical models and through coordinated research, we have now achieved a reasonably high skill for monsoon prediction in different time scales. In the endeavour, ESSO-IITM has coordinated the Mission as a nodal agency and contributed for seasonal and extended range predictions of monsoon with support from ESSO-NCMRWF for atmospheric initial conditions and ESSO-INCOIS for ocean initial conditions and finally transferred the modelling system to ESSO-IMD for operational use. ESSO-NCMRWF has contributed for short to medium range forecasts in association with ESSO-IITM and the modelling system has been transferred to ESSO-IMD for operational use. ESSO-IITM and ESSO-INCOIS have contributed for development of coupled data assimilation system in association with University of Maryland, USA. These show beautiful examples of coordinated research work for achieving an useful goal. Thus, through **Monsoon Mission Phase-1**, we have **achieved very important goals**. Some of the **important achievements** are as follows:

1. One of the best seasonal prediction models (in the world) for predicting rainfall with the highest resolution of 38 Km (in horizontal for atmosphere), so far unparalleled.
2. Skilful prediction of monsoon active/break cycles at extended range, at par with the best in the world.
3. Very high resolution (~27 Km in horizontal) weather forecasts at short and medium range, resulting in gain of 2 days lead time.
4. Coupled data assimilation system, which improves the quality of initial conditions required by dynamical models.
5. Transferred all the forecast models to ESSO-IMD to operationalize (so that there can be operational use of these models for delivering forecasts to the nation). Thus, ESSO-IMD is now having models for prediction in different time scales (2-10 days, 10-20 days as well as monthly to seasonal scales). This will be very useful for various sectors, like agriculture, hydrology, etc.
6. Setting up of High performance Computing system (1.2 PF in MoES, mainly at IITM & NCMRWF).

Gap Areas:

1. **Dry bias over Indian land mass:** It still remains and several diagnostics studies have suggested that anomalous anticyclonic circulation over Indian land mass is supressing the rainfall there due to cold SST bias surrounding the Indian land mass and weak cross equatorial flow.

2. **Cold SST bias**: The excessive evaporation due to drier atmosphere and misrepresentation of ocean advection terms results in cold SST bias in the Indian Ocean region. High resolution modelling efforts (T382) have reduced the cold SST bias particularly in the Indian Ocean.

3. **Indian Ocean Teleconnections with ISMR**: The ISMR rainfall generally correlates positively with warm (cold) SST anomalies over western (eastern) equatorial Indian Ocean in observations. However, in the model the relation is just opposite (i.e., cold (warm) SST anomalies over western (eastern) equatorial Indian Ocean). In order to further improve the skill of the model this bias needs to be either removed or reduced. High resolution model experiments and ESM model simulations have clearly demonstrated that the biases reduce.

Further work is required to get proper phase and amplitude of these teleconnections in the model.

4. **Overestimation of convective rainfall:** Convective rainfall is overestimated in the model and large-scale precipitation is underestimated. Some attempts to reduce these biases include super parametrization, cloud microphysics, multi cloud multi scale parametrization techniques in addition to high resolution modelling.

5. **Cold Troposphere:** Most of the troposphere is cooler compared to observations and recent attempts of super parametrization, cloud microphysics, multi cloud multi scale parametrization techniques have resulted in reducing this bias significantly.

6. **Thick snow and late melting of Eurasian Snow:** The simulated snow depth over Eurasian region is almost twice to that of the observation and melting of snow is delayed by a month. However, the model captures the inverse relation between ISMR and the Eurasian snow. Multilayer snow scheme developed in-house showed promising results in reduced thickness of the snow and reduced dry bias over the India.

The **second phase of Monsoon Mission has just started with following future directions**:

1. To fully develop an Indigenous Monsoon Mission Model, incorporating the present achievements in the model development.
2. To develop an Unified Model, based on the above model by incorporating the regional models in the above model, so that weather/ climate extremes can be predicted with improved accuracy and seamlessly (seamless prediction system).
3. To develop weather and climate applications for agriculture, hydrology, etc.

Recommendations by different monitoring committees:

The SRMC, SSC, IPC and IPRC committees (minutes of 7 each SRMC, SSC and one IPC and IPRC are attached as annexure 2) appreciated the excellent model development efforts of the MoES institutions for improving the Indian forecast system (for short and medium range, extended range and seasonal) during the past five years and recommended that the monsoon mission should continue its good work in the future also. Thus the committee recommended monsoon mission phase 2 with focus on developing applications with social impacts (eg: agriculture, hydrology, solar/wind energy). Meanwhile developmental activities should also go hand in hand to improve the prediction of extremes at all the different time scales. Since these additional works need development of applications etc, enough manpower should be projected and same may be made available during the next phase.

The monsoon mission phase 2 need to provide the short range, extended range and long range forecast at the different stage of the agriculture from seeding, crop growth and harvesting etc.

The committee also recommended to check the monsoon mission approach adopted for the program was correct or not and the corrections need to be implemented.

The committees also recommended that the modified CFS with inputs from the different projects should be made as base model and a document on the model should be prepared.

As the foreign projects have done good contributions to the phase 1 of monsoon mission, no-coast extension should be given to these projects so that the PIs can get enough time to deliver project objectives and prepare completion report.

The committees also noted that for the further developments in the model development activity grossly depend on the HPC resources available to the mission and recommended for the upgrading of HPC in phase 2.

Another major recommendation is that modeling development should focus on some areas like developing land data assimilation system, study of diurnal cycle representation in GFS/CFS compared with NERC observations, study of water covered are in land using NERSC data etc. This is needed as the projects in the first phase has indicted about the potential of land use for improving the forecast at extended range as well as for seasonal prediction. The weakly coupled data assimilation system also needs to be systematically tested during these periods. There should be a separate committee to decide the working strategy for these developmental activates.

Committees also felt that a short term course on monsoon mission model should be arranged to encourage the young scientists from across various organizations to participate in the next phase of monsoon mission.

There should be a program management office should be set up which can constantly monitor the implementation and progress of the mission in second phase. The office can keep track on the model code development and can made and release documents as the different versions are released/implemented.

There should be committee meeting in February in two different sessions.

The committee also recommended recruitment of additional manpower in phase 2 without re designation and proposed different pay scales also.

ANNEXURE-1

Publications under Monsoon Mission

(A)IITM publications, based on CFS and related models, during 2012-2017

Publications - 2012

1. Pokhrel S., Chaudhari H.S., Saha S.K., Dhakate A., Yadav R.K., Salunke K., Mahapatra S., Suryachandra A. Rao, ENSO, IOD and Indian summer monsoon in NCEP climate forecast system, Climate Dynamics, 39, November 2012, DOI:10.1007/s00382-012-1349-5, 2143-2165

2. Pokhrel S., Rahaman H., Parekh A., Saha S.K., Dhakate A., Chaudhari H.S., Gairola R.M., Evaporation-precipitation variability over Indian Ocean and its assessment in NCEP Climate Forecast System (CFSv2), Climate Dynamics, 39, November 2012, DOI:10.1007/s00382-012-1542-6, 2585-2608.

3. Samala B.K., Krishnan R., Roxy M., Assessment of one month forecasts of weak Indian monsoons based on the NCEP climate forecast system,Meteorological Applications, 19, June 2012, DOI: 10.1002/met.1331, 189-199.

Publications - 2013

4. Abhilash S., Sahai A.K., Pattnaik S., De S., 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, August 2013, DOI:10.1016/j.jastp.2013.03.017, 13-23.

5. Chowdary J.S., Chaudhari H.S., Gnanaseelan C., Parekh A., Rao Suryachandra A., Sreenivas P., Pokhrel S., Singh P.,Summer monsoon circulation and precipitation over the tropical Indian Ocean during ENSO in the NCEP climate forecast system, Climate Dynamics, online, June 2013, DOI:10.1007/s00382-013-1826-5, 1-23.

6. Pattnaik S., Abhilash S., De S., Sahai A.K., Phani R., Goswami B.N., Influence of convective parameterization on the systematic errors of Climate Forecast System (CFS) model over the Indian monsoon region from an extended range forecast perspective, Climate Dynamics, 41, July 2013, DOI:10.1007/s00382-013-1662-7, 341–365.

7. Saha Subodh K., Pokhrel S., Chaudhari H.S., Dhakate A., Shewale S., Sabeerali C.T., Salunke K., Hazra A., Mahapatra S., Suryachandra A. Rao, Improved simulation of Indian summer monsoon in latest NCEP climate forecast system free run, International Journal of Climatology, online, July 2013, DOI:10.1002/joc.3791, 1-14.

8. Sooraj K.P., Seo K-H, Boreal summer intra-seasonal variability simulated in the NCEP climate forecast system: insights from moist static energy budget and sensitivity to convective moistening, Climate Dynamics, 41, September 2013, DOI: 10.1007/s00382-012-1631-6, 1569-1594.

9. Chaudhari H.S., Pokhrel S., Mohanty S., Saha S.K., Seasonal prediction of Indian summer monsoon in NCEP coupled and uncoupled model,Theoretical and Applied Climatology,114, November 2013, DOI:10.1007/s00704-013-0854-8, 459-477.

10. Chaudhari H.S., Pokhrel S., Saha S.K., Dhakate A., Yadav R.K., Salunke K., Mahapatra S., Sabeerali C.T., Suryachandra A. Rao, Model biases in long coupled runs of NCEP CFS in the context of Indian summer monsoon, International Journal of Climatology, 33, April 2013, DOI:10.1002/joc.3489, 1057-1069.

11. Pokhrel S., Dhakate A., Chaudhari H.S., Saha S.K., Status of NCEP CFS vis-a-vis IPCC AR4 models for the simulation of Indian summer monsoon, Theoretical and Applied Climatology, 111, January 2013, DOI:10.1007/s00704-012-0652-8, 65-78.

12. Saha Subodh K., Pokhrel S., Chaudhari H.S., Influence of Eurasian snow on Indian summer monsoon in NCEP CFSv2 freerun, Climate Dynamics, 41, October 2013, DOI:10.1007/s00382-012-1617-4, 1801-1815.

13. Sahai A.K., Sharmila S., Abhilash S., Chattopadhyay R., Borah N., Krishna R.P.M.,Joseph Susmitha, Roxy M., De S., Pattnaik S., Pillai P.A., Simulation and Extended range prediction of Monsoon Intra-seasonal Oscillations in NCEP CFS/GFS version 2 framework, Current Science, 104, May 2013, 1394-1408.

14. C.T. Sabeerali, R.A. Dandi, A.R. Dhakate, K.Salunke, S. Mahapatra and S.A. Rao, 2013: Simulation of boreal summer intraseasonal oscillations in the latest CMIP5 coupled GCMs, Journal of Geophysical Research, DOI:10.1002/jgrd.50403.

Publication - 2014

15. Abhilash S., Sahai A. K., Pattnaik S., Goswami B.N., Arun Kumar, 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, January 2014, DOI:10.1002/joc.3668, 98-113.

16. Abhilash S., Sahai A. K., Pattnaik S., Goswami B.N., Arun Kumar, 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, June 2014, DOI:10.1002/asl2.477, 114–119.

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

18. Borah N., Sahai A. K., Abhilash S., Chattopadhyay R. , Joseph S., Sharmila S., Kumar A., Assessment of real-time extended range forecast of 2013 Indian summer monsoon, International Journal of Climatology, online, October 2014, DOI:10.1002/joc.4178, 1-17.

19. Chaudhari H.S., Pokhrel S., Saha Subodh K., Dhakate A., Hazra A., Improved depiction of Indian summer monsoon in latest high resolution NCEP climate forecast system reanalysis, International Journal of Climatology, online, November 2014, DOI:10.1002/joc.4196, 1-18.

20. Chowdary J.S., Chaudhari H.S., Gnanaseelan C., Parekh A., Rao Suryachandra A., Sreenivas P., Pokhrel S., Singh P., Summer monsoon circulation and precipitation over the tropical Indian Ocean during ENSO in the NCEP climate forecast system, Climate Dynamics, 42, April 2014, DOI:10.1007/s00382-013-1826-5, 1925-1947.

21. Ganai M., Mukhopadhyaya P., Phani Murali Krishna R., Mahakur M., Impact of revised simplified Arakawa–Schubert convection parameterization scheme in CFSv2 on the simulation of the Indian summer monsoon, Climate Dynamics, online, September 2014, DOI:10.1007/s00382-014-2320-4, 1-22.

22. Goswami B.B., Deshpande M.S., Mukhopadhyay P., Saha Subodh K., Rao Suryachandra A., Murthugudde R., Goswami B.N., Simulation of monsoon intra-seasonal variability in NCEP CFSv2 and its role on systematic bias, Climate Dynamics, 43, November 2014, DOI:10.1007/s00382-014-2089-5, 2725-2745.

23. Saha Subodh K., Pokhrel S., Chaudhari H.S., Dhakate A., Shewale S., Sabeerali C.T., Salunke K., Hazra A., Mahapatra S., Suryachandra A. Rao, Improved simulation of Indian summer monsoon in latest NCEP climate forecast system free run, International Journal of Climatology, 34, April 2014, DOI:10.1002/joc.3791,1628–1641.

24. Sahai A.K., Abhilash S., Chattopadhyay R., Borah N., Joseph S., Sharmila S, Rajeevan M., High-resolution operational monsoon forecasts: an objective assessment, Climate Dynamics, online, June 2014, DOI:10.1007/s00382-014-2210-9, 1-12.

Publication - 2015

25. Hazra A, Chaudhari H.S., A.S. Rao., Goswami B.N., Dhakate A., Pokhrel S., Saha S.K., Impact of revised cloud microphysical scheme in CFSv2 on the simulation of the Indian summer monsoon. International Journal of Climatology. DOI: 10.1002/joc.4320 December 2015,Vol 35, PP4738-4755.

26. Abhilash S., Sahai A. K., Borah N., Joseph S., Chattopadhyay R., Sharmila S., Rajeevan M., Mapes B. and Arun Kumar, Improved spread-error relationship and probabilistic prediction from CFS based grand ensemble system, Journal of Applied Meteorology and Climatology, 2015, accepted on 14 April 2015.

27. Chaudhari H.S., S. Pokhrel, H. Rahman, A. Dhakate, S. K. Saha, S. Pentakota, Gairola R.M., Influence of upper ocean on Indian summer monsoon rainfall : Studies by observation and NCEP Climate Forecast System (CFSv2), Theoretical and Applied Climatology, DOI 10.1007/s00704-015-1521-z May 2015.

28. Chattopadhyay Rajib, R. Phani, C. T. Sabeerali, A. R. Dhakate, K. Salunke, S. Mahapatra, A. Suryachandra Rao, and B. N. Goswami, Influence of Extra-tropical Sea Surface Temperature on the Indian summer Monsoon: An unexplored source of seasonal predictability, Quarterly Journal of the Royal Meteorological Society (QJRMS), DOI:10.1002/qj.2562.

29. Chowdary J.S., Parekh A., Ojha S., Gnanaseelan C., Role of upper ocean processes in the seasonal SST evolution over tropical Indian Ocean in climate forecasting system, Climate Dynamics, online, January 2015, DOI:10.1007/s00382-015-2478-4, 1-19.

30. Bidyut B. Goswami, R. P. M. Krishna, P. Mukhopadhyay, Marat Khairoutdinov, and B. N. Goswami, Simulation of the Indian Summer Monsoon in the Super-parameterized Climate Forecast System Version 2: Preliminary Results. J. Climate,Vol: 28, Issue:21, November, 8988–9012. doi: http://dx.doi.org/10.1175/JCLI-D-14-00607.1.

31. Chaudhari H. S., S. Pokhrel, A. Kulkani, A. Hazra, S. K. Saha, Clouds-SST relationship and inter-annual variability modes of Indian summer monsoon in the context of clouds and SSTs: Observational and modelling aspects, International Journal of Climatology, DOI: 10.1002/joc.4664. February 2016.

32. Saha S. K., S. Pokhrel, K. Salunke, A. Dhakate, H. S. Chaudhari, H. Rahman, K. Sujith, A. Hazra, D. R. Sikka, Potential Predictability of Indian Summer Monsoon Rainfall in NCEP CFSv2, Journal of Advances in Modeling Earth Systems, DOI:10.1002/2015MS000542. February 2016.

33. Saha S. K., K. Sujith, S. Pokhrel, H. S. Chaudhari, A. Hazra, Predictability of global monsoon rainfall in NCEP CFSv2, Climate Dynamics, DOI:10.1007/s00382-015-2928-z. December 2015.

34. Chattopadhyay R., Suryachandra A. Rao, Sabeerali C.T., George G., Rao Nagarjuna D., Dhakate A., Salunke K., Large-scale teleconnection patterns of Indian summer monsoon as revealed by CFSv2 retrospective seasonal forecast runs, International Journal of Climatology, online, December 2015, DOI:10.1002/joc.4556, 1-17.

Publication -2016

35. Abhik S., Mukhopadhyay P., Krishna R.P.M., Salunke K.D., Dhakate A.R., Suryachandra A. Rao, Diagnosis of boreal summer intra-seasonal oscillation in high resolution NCEP climate forecast system, Climate Dynamics, 46, May 2016, DOI:10.1007/s00382-015-2769-9, 3287-3303.

36. Chaudhari H.S., Hazra A., Saha Subodh K., Dhakate A., Pokhrel S., Indian summer monsoon simulations with CFSv2: a microphysics perspective, Theoretical and Applied Climatology, 125, July 2016,DOI:10.1007/s00704-015-1515, 253-269.

37. Chaudhari H.S., Pokhrel S., Kulkarni Aiay, Hazra A., Subodh Kumar Saha, Clouds SST relationship and inter-annual variability modes of Indian summer monsoon in the context of clouds and SSTs:observational and modelling aspects, International Journal of Climatology, online, February 2016, DOI:10.1002/joc.4664, 1-18.

38. De S., Hazra A., Chaudhari H.S., Does the modification in "critical relative humidity" of NCEP CFSv2 dictate Indian mean summer monsoon forecast? Evaluation through thermo-dynamical and dynamical aspects, Climate Dynamics, 46, February 2016, DOI:10.1007/s00382-015-2640-z, 1197-1222.

39. George G., Rao Nagarjuna D., Sabeerali C.T., Srivastava Ankur, Suryachandra A. Rao, Indian summer monsoon prediction and simulation in CFSv2 coupled model, Atmospheric Science Letters, 17, January 2016, DOI:10.1002/asl.599, 57-64.

40. Halder M., Mukhopadhyay P., Microphysical processes and hydrometeor distributions associated with thunderstorms over India: WRF (cloud-resolving) simulations and validations using TRMM, Natural Hazards, online, June 2016, DOI:10.1007/s11069-016-2365-2, 1-31.

41. Hazra A., Chaudhari H.S., Dhakate A., Evaluation of cloud properties in the NCEP CFSv2 model and its linkage with Indian summer monsoon, Theoretical and Applied Climatology, 124, April 2016, DOI:10.1007/s00704-015-1404-3, 31-41.

42. Hazra A., Chaudhari H.S., Pokhrel S., Saha Subodh K., Indian summer monsoon precipitating clouds: role of microphysical process rates, Climate Dynamics, 46, April 2016, DOI:10.1007/s00382-015-2717-8, 2551-2571.

43. Joseph S., Sahai A. K., Chattopadhyay R., Sharmila S., Abhilash S., Rajeevan M., Mandal R., Dey A., Borah N., Phani R., Extremes in June rainfall during Indian summer monsoons of 2013 and 2014: Observational Analysis and Extended range prediction, Quarterly Journal of Royal Meteorological Society, 142, April 2016, DOI:10.1002/qj.2730, 1276-1289.

44. Pokhrel S., Saha Subodh K., Dhakate A., Rahman H., Chaudhari H.S., Salunke K., Hazra A., Sujith K., Sikka D.R., Seasonal prediction of Indian summer monsoon rainfall in NCEP CFSv2: forecast and predictability error, Climate Dynamics, 46, April 2016, DOI:10.1007/s00382-015-2703-1, 2305-2326.

45. Ramu D. A., Sabeerali C. T., Chattopadhyay R., Rao D. N., George G., Dhakate A. R., Salunke K., Srivastava A., Suryachandra A. Rao, Indian summer monsoon rainfall simulation and prediction skill in the CFSv2 coupled model: Impact of atmospheric horizontal resolution, Journal of Geophysical Research, 121, March 2016, DOI:10.1002/ 2015JD024629, 1-17.

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

47. SnehlataTirkey and P. Mukhopadhyay, 2016, Evaluation of NCEP TIGGE short-range forecast for Indian summer monsoon intra-seasonal oscillation, Theor. Appl. Climatol., Online published on 30 April 2016, DOI: 10.1007/s00704-016-1811-0, 1-37.

48. Pillai P.A., Rao S.A., George G., Rao D.N., Mahapatra S., Rajeevan M., Dhakate A., Salunke K., How distinct are the two flavors of El Niño in retrospective forecasts of Climate Forecast System version 2 (CFSv2)?, Climate Dynamics, online, August 2016, DOI:10.1007/s00382, 1-26-016-3305-2, 1-26.

49. Pillai P.A., Chowdary J.S., Indian summer monsoon intra-seasonal oscillation associated with the developing and decaying phase of El Niño, International Journal of Climatology, 36, March 2016, DOI:10.1002/joc.4464, 1846-1862.

50. Goswami, B.N., S.A. Rao, D. Sengupta, and S. Chakravorty. 2016, Monsoons to Mixing in the Bay of Bengal: Multiscale Air-Sea Interactions and Monsoon Predictability, Oceanography 29(2):18–27.

51. Pradhan, M., Yadav, R.K., Ramu Dandi, A., Srivastava, A., Phani, M.K. and Rao, S.A**.,** 2016, Shift in MONSOON–SST teleconnections in the tropical Indian Ocean and ENSEMBLES climate models' fidelity in its simulation, International Journal of Climatology,doi:10.1002/joc.4841.

52. Ganai M., Krishna R.P.M., Mukhopadhyay P., Mahakur M., 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, published Online, August 2016, doi: 10.1002/2016JD025393, 1-50.

53. Chaudhari H.S**.**, S. Pokhrel, H. Rahman, A. Dhakate, S. K. Saha, S. Pentakota, Gairola R.M., 2016: Influence of upper ocean on Indian summer monsoon rainfall : Studies by observation and NCEP Climate Forecast System (CFSv2), Theoretical and Applied Climatology, 125:413-426.

54. B. B. Goswami, B. Khouider, R. Phani, P. Mukhopadhyay and Andrew Majda, 2016: Improving Synoptic and Intra-Seasonal Variability in CFSv2 via Stochastic Representation ofOrganized Convection, Geophysical Research Letter, November, Doi:10.1002/ 2016GL071542.

55. Chaudhari H.S., Pokhrel S., Rahman H., Dhakate A., Saha Subodh K., Pentakota S., Gairola R.M. “Influence of upper ocean on Indian summer monsoon rainfall: studies by observation and NCEP climate forecast system(CFSv2)”, Theoretical and Applied Climatology, 125, August 2016, DOI:10.1007/s00704-015-1521-z, 413–426.

56. Pillai P.A., Sahai A.K**.,** Moisture dynamics of the northward and eastward propagating boreal summer intraseasonal oscillations: possible role of tropical Indo-west Pacific SST and circulation**,** Climate Dynamics, 47, August 2016, 1335–1350.

57. Saha Subodh K., Sujith K., Pokhrel S., Chaudhari H. S., Hazra A**.**, Predictability of Global Monsoon Rainfall in NCEP CFSv2, Climate Dynamics, 47, September 2016, DOI:10.1007/s00382-015-2928-z, 1693–1715.

58. Arora A., Suryachandra A. Rao, Chattopadhyay R., Goswami T., George G., Sabeerali C.T.,Role of Indian Ocean SST variability on the recent global warming hiatus, Global and Planetary Change,"143, August 2016, 21-30.

59. Chakravorty S., Gnanaseelan C., Pillai P.A.,Combined influence of remote and local SST forcing on Indian Summer Monsoon Rainfall variability" Climate Dynamics, 47, October 2016, DOI:10.1007/s00382-016-2999-5, 2817-2831.

60. Chattopadhyay R., Suryachandra A. Rao, Sabeerali C.T., George G., Rao Nagarjuna D., Dhakate A., Salunke K**.**, Large-scale teleconnection patterns of Indian summer monsoon as revealed by CFSv2 retrospective seasonal forecast runs, International Journal of Climatology, 36, July 2016, DOI:10.1002/joc.4556, 3297–3313.

61. Chowdary J.S., Harsha H.S., Gnanaseelan C., Srinivas G., Parekh A., Pillai P., andNaidu C.V**.,**Indian summer monsoon rainfall variability in response to differences in the decay phase of El Niño,Climate Dynamics, online, June 2016, DOI:10.1007/s00382-016-3233-1, 1-21.

62. Halder S., SahaSubodh K., Dirmeyer P.A., Chase T.N., andGoswami B.N., Investigating the impact of land-use land-cover change on Indian summer monsoon daily rainfall and temperature during 1951–2005 using a regional climate model, Hydrology and Earth System Sciences, May 2016, DOI:10.5194/hess-20-1765-2016, 1765–1784.

63. Hazra A., Padma kumari B., Maheskumar R.S.,and Chen J-P, Effect of mineral dust and soot aerosols on ice microphysics near the foothills of the Himalayas: A numerical investigation,Atmospheric Research, May 2016, DOI:10.1016/j .atmosres.2015.12.005, Vol. 171, pp 41–55.

64. Siddharth Kumar, Anika Arora, R.Chattopadhyay, AnupamHazra, SuryachandraA.Rao, andB.N.Goswami, Seminal role of stratiform clouds in large-scale aggregation of tropical rain in boreal summer monsoon intra-seasonal oscillations**,**Climate Dynamics**,** published online: 16 April 2016, DOI 10.1007/s00382-016-3124-5, 1-17, Impact Factor 4.673.

65. Chakravorty Soumi, C. Gnanaseelanand P.A. Pillai, Combined Influence of Remote and Local SST forcing on Indian Summer Monsoon Rainfall Variability, Climate Dynamics, January 2016, published online, DOI:10.1007/s00382-016-2999-5, 1-15.

Publication -2017

66. Dandi A. Ramu, Suryachadra A. Rao, Prasanth A. Pillai, M. Pradhan, G. George, D. Nagarguna Rao, S. Mahapatra,D. S. Pai and M. Rajeevan**,** 2017, Prediction of seasonal summer monsoon rainfall over homogenous regions of India using dynamical prediction system"**,** Journal of Hydrology (Accepted on 7th January, 2017).

67. Hazra A., H. S. Chaudhari, M. Ranalkar, J. P. Chen, 2017: Role of interactions between cloud microphysics, dynamics and aerosol in the heavy rainfall event of June 2013 over Uttarakhand, India,Journal of Advances in Modelling Earth Systems 10.1002/qj.2983.

68. Saha S. K., K. Sujith, S. Pokhrel, H. S. Chaudhari, and A. Hazra, 2017,Effects of multilayer snow scheme on the simulation of snow: Offline Noah and coupled with NCEP CFSv2, Journal of Advances in Modeling Earth Systems (JAMES**)**, DOI: 10.1002/2016MS000845.(published 30 January 2017).

69. Abhik S., Krishna R.P.M., Mahakur M., Ganai M., Mukhopadhyay P., Dudhia J (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, May 2017

70. Goswami B.B., Khouider B., Phani R., Mukhopadhyay P., Majda A. (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, July 2017

71. Goswami B.B., 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, October 2017

72. Goswami T., Suryachandra A. Rao, Hazra A., Chaudhari H.S., Dhakate A., Salunke K., Mahapatra S. (2017). Assessment of simulation of radiation in NCEP Climate Forecasting System (CFS V2). Atmospheric Research, 193, September 2017,

73. Hazra A., Chaudhari H.S., Saha Subodh K., Pokhrel S., 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, October 2017,

74. 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, September 2017,

75. Srinivas G., Chowdary J.S., Gnanaseelan C., Prasad K.V.S.R., Karmakar A., Parekh A. (2017). Association between mean and interannual equatorial Indian Ocean subsurface temperature bias in a coupled model Climate Dynamics, online, May 2017

76. Srivastava Ankur, Rao Suryachandra A., Rao Nagarjuna D., George G., Pradhan M. (2017). Structure, characteristics, and simulation of monsoon low-pressure systems in CFSv2 coupled model. ournal of Geophysical Research, 122, August 2017

77. Terray P., Sooraj K.P., Masson S., Krishna R.P.M. (2017). Towards a realistic simulation of boreal summer tropical rainfall climatology in state-of-the-art coupled models: role of the background snow-free land albedo. Climate Dynamics, online, July 2017

78. Pradhan M., Suryachandra A. Rao, Srivastava Ankur, Dakate A., Salunke K., Shameera K.S. (2017) Prediction of Indian Summer-Monsoon Onset Variability: A Season in Advance. Scientific Reports, 7:14229, October 2017

(B) Publications, from National & International projects of the Monsoon Mission, during 2012-2017:

1. J. Lucas, E. L. Shroyer, H. W. Wijesekera, H. J. S. Fernando, E. D. Asaro, M.Ravichandran, S. U. P. Jinadasa, J. A. Mackinnon, J. D. Nash, R. Sharma, L.Centurioni, J. T. Farrar, R. Weller, R. Pinkel, A. Mahadevan, D. Sengupta, andA. Tandon, (2014), Mixing to Monsoons: Air-Sea Interactions in the Bay ofBengal, EOS, Vol. 95, No. 30, 29 July 2014.

2. Sahu, K. C., & Govindarajan, R. (2014). Instability of a free-shear layer inthe vicinity of a viscosity-stratified layer. Journal of Fluid Mechanics, 752, 626-648.

3. D. Sengupta, A. Tandon, E. Shroyer and M. Ravichandran. 2015. The OMMASIRI Initiative in the Bay of Bengal. CLIVAR Exchanges 19(3), 35-37.

4. Pant, V., M. S. Girishkumar, T. V. S. Udaya Bhaskar,M. Ravichandran, F.Papa, V. P. Thangaprakash (2015), Observed inter-annual variability of nearsurfacesalinity in the Bay of Bengal, J. Geophys. Res. Oceans, 120,doi:10.1002/2014JC010340.

5. Ravichandran, S., & Govindarajan, R. (2015). Caustics and clustering in thevicinity of a vortex.Physics of Fluids (1994-present), 27(3), 033305.

6. Wijesekera, H., E. Shroyer, A. Tandon, M. Ravichandran, D. Sengupta, S.Jinadasa, H. Fernando, N. Agrawal, K. Arulananthan, G. Bhat, M. Baumgartner,J. Buckley, L. Centurioni, P. Conry, J. Farrar, A. Gordon, V. Hormann, E. Jarosz,T. Jensen, S. Johnston, M. Lankhorst, C. Lee, L. Leo, I. Lozovatsky, A. Lucas, J.Mackinnon, A. Mahadevan, J. Nash, M. Omand, H. Pham, R. Pinkel, L.Rainville, S. Ramachandran, D. Rudnick, S. Sarkar, U. Send, R. Sharma, H.Simmons, K. Stafford, L. St. Laurent, K. Venayagamoorthy, R. Venkatesan, W.Teague, D. Wang, A. Waterhouse, R. Weller, and C. Whalen, 2016, ASIRI: AnOcean-Atmosphere Initiative for Bay of Bengal. Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-14-00197.1.

7. Sengupta, D., Bharath Raj, G. N., Ravichandran, M., Sree Lekha, J., & Papa,F. (2016). Near-surface salinity and stratification in the north Bay of Bengalfrom moored observations. Geophysical Research Letters, 43(9), 4448-4456.

8. Mathur, M., Carter, G. S., & Peacock, T. (2016). Internal tide generationusing Green function analysis: to WKB or not to WKB?.Journal of PhysicalOceanography, (2016).

9. Tandon, A., E.A. D'Asaro, K.M. Stafford, D. Sengupta, M. Ravichandran, M.Baumgartner, R. Venkatesan, and T. Paluszkiewicz. 2016, Technologicaladvancements in observing the upper ocean in the Bay of Bengal: Education and capacity building, Oceanography 29(2):242-253.

10. Bhat, G.S., and H.J.S. Fernando. 2016. , Remotely driven anomalous seaairheat flux over the north Indian Ocean during the summer monsoon season. ,Oceanography 29(2):232-241.

11. Goswami, B.N., S.A. Rao, D. Sengupta, and S. Chakravorty. 2016, Monsoons to mixing in the Bay of Bengal: Multiscale air-sea interactions andmonsoon predictability., Oceanography 29(2):18-27.

12. Chowdary, J.S., G. Srinivas, T.S. Fousiya, A. Parekh, C. Gnanaseelan, H.Seo, and J.A. MacKinnon. 2016. Representation of Bay of Bengal upper-oceansalinity in general circulation models. , Oceanography 29(2):38-49.

13. Sharma, R., N. Agarwal, A. Chakraborty, S. Mallick, J. Buckley, V. Shesu,and A. Tandon. 2016. , Large-scale air-sea coupling processes in the Bay ofBengal using space-borne observations. , Oceanography 29(2):192-201.

14. Thangaprakash, V.P., M.S. Girishkumar, K. Suprit, N. Suresh Kumar, D.Chaudhuri, K. Dinesh, A. Kumar, S. Shivaprasad, M. Ravichandran, J.T. Farrar,R. Sundar, and R.A. Weller. 2016. What controls seasonal evolution of seasurface temperature in the Bay of Bengal?

Mixed layer heat budget analysisusing moored buoy observations along 90E. ,Oceanography 29(2):202-213.

15. Lotliker, A.A., M.M. Omand, A.J. Lucas, S.R. Laney, A. Mahadevan, andM. Ravichandran. 2016. Penetrative radiative flux in the Bay of Bengal,Oceanography 29(2):214-221.

16. Sarma, V.V.S.S., G.D. Rao, R. Viswanadham, C.K. Sherin, J. Salisbury,M.M. Omand, A. Mahadevan, V.S.N. Murty, E.L. Shroyer, M. Baumgartner, andK.M. Stafford. 2016. Effects of freshwater stratification on nutrients, dissolvedoxygen, and phytoplankton in the Bay of Bengal. , Oceanography 29(2):222-231.

17. Johnston, T.M.S., D. Chaudhuri, M. Mathur, D.L. Rudnick, D. Sengupta,H.L. Simmons, A. Tandon, and R. Venkatesan. 2016. Decay mechanisms ofnear-inertial mixed layer oscillations in the Bay of Bengal. , Oceanography29(2):180-191.

18. Mahadevan, A., T. Paluszkiewicz, M. Ravichandran, D. Sengupta, and A.Tandon. 2016. Introduction to the special issue on the Bay of Bengal: Frommonsoons to mixing. , Oceanography 29(2):14-17.

19. Weller, R.A., J.T. Farrar, J. Buckley, S. Mathew, R. Venkatesan, J. SreeLekha, D. Chaudhuri, N. Suresh Kumar, and B. Praveen Kumar. 2016. Air-seainteraction in the Bay of Bengal. , Oceanography 29(2):28-37.

20. MacKinnon, J.A., J.D. Nash, M.H. Alford, A.J. Lucas, J.B. Mickett, E.L.Shroyer, A.F. Waterhouse, A. Tandon, D. Sengupta, A. Mahadevan, M.Ravichandran, R. Pinkel, D.L. Rudnick, C.B. Whalen, M.S. Alberty, J. SreeLekha, E.C. Fine, D. Chaudhuri, and G.L. Wagner. 2016. A tale of two spicyseas. , Oceanography 29(2):50-61.

21. Shroyer, E.L., D.L. Rudnick, J.T. Farrar, B. Lim, S.K. Venayagamoorthy,L.C. St. Laurent, A. Garanaik, and J.N. Moum. 2016. Modification of upperoceantemperature structure by subsurface mixing in the presence of strongsalinity stratification, Oceanography 29(2):62-71.

22. Mahadevan, A., G. Spiro Jaeger, M. Freilich, M. Omand, E.L. Shroyer, andD. Sengupta. 2016. Freshwater in the Bay of Bengal: Its fate and role in air-sea heat exchange, Oceanography 29(2):72-81

23. Gordon, A.L., E.L. Shroyer, A. Mahadevan, D. Sengupta, and M. Freilich. 2016, Bay of Bengal: 2013 northeast monsoon upper-ocean circulation,Oceanography 29(2):82-91.

24. Jensen, T.G., H.W. Wijesekera, E.S. Nyadjro, P.G. Thoppil, J.F. Shriver,K.K. Sandeep, and V. Pant. 2016. Modeling salinity exchanges between theequatorial Indian Ocean and the Bay of Bengal. , Oceanography 29(2):92-101.

25. Hormann, V., L.R. Centurioni, A. Mahadevan, S. Essink, E.A. D'Asaro, andB. Praveen Kumar. 2016. Variability of near-surface circulation and sea surfacesalinity observed from Lagrangian drifters in the northern Bay of Bengal duringthe waning 2015 southwest monsoon. , Oceanography 29(2):124-133.

26. Lucas, A.J., J.D. Nash, R. Pinkel, J.A. MacKinnon, A. Tandon, A.Mahadevan, M.M. Omand, M. Freilich, D. Sengupta, M. Ravichandran, and A.Le Boyer. 2016. Adrift upon a salinity-stratified sea: A view of upper-oceanprocesses in the Bay of Bengal during the southwest monsoon, Oceanography, 29(2):134-145.

27. Sarkar, S., H.T. Pham, S. Ramachandran, J.D. Nash, A. Tandon, J. Buckley,A.A. Lotliker, and M.M. Omand. 2016. The interplay between submesoscaleinstabilities and turbulence in the surface layer of the Bay of Bengal,Oceanography 29(2):146-157.

28. Warner, S.J., J. Becherer, K. Pujiana, E.L. Shroyer, M. Ravichandran, V.P.Thangaprakash, and J.N. Moum. 2016, Monsoon mixing cycles in the Bay of Bengal: A year-long subsurface mixing record, Oceanography 29(2):158-169.

29. Parampil, S. R., Bharathraj, G. N., Harrison, M., & Sengupta, D. (2016). Observed subseasonal variability of heat flux and the SST response of the tropical Indian Ocean. Journal of Geophysical Research: Oceans.

30. Venugopal, V., & Wallace, J. M. (2016). Climatology of Contributionweighted Tropical Rain Rates based on TRMM 3B42. Geophysical Research Letters.

31. S.S.V.S.Ramakrishna,V.Brahmananda Rao, B.R.SrinivasaRao.,D.HariPrasad.,N.NanajiRao.,RoshmithaPanda, (2016), A study of 2014 record drought in India with CFSv2 model: role of water vapour transport. **Climate Dynamics**. DOI10.1007/s00382-016-3343-9.

32. Shahi, N. K., Rai, S., & Pandey, D. K. (2016). Prediction of daily modes of South Asian monsoon variability and its association with Indian and Pacific Ocean SST in the NCEP CFS V2. *Meteorology and Atmospheric Physics*,***128*****(1)**, 131–142.

33. Pandey, D. K., Rai, S., Sahai, A. K., Abhilash, S., & Shahi, N. K. (2016). Prediction and error growth in the daily forecast of precipitation from the NCEP CFSv2 over the subdivisions of Indian subcontinent. *Journal of Earth System Science*, **125(1)**, 29–45.

34. Rai, S., Kucharski, F., & Molteni, F. (2016). An analysis of the impact of SST drift in the ECMWF system 3 on simulation of the Indian summer climatology. *Meteorology and Atmospheric Physics*, 1–10.

35. Shahi, N. K., Rai, S., Pandey, D. K., & Mishra, N. (2015). Seasonal prediction skill of Indian summer monsoon rainfall in ECMWF system 4 model. *Climate Change*, **1(4)**, 469–475.

36. Pandey, D. K., Rai, S., Shahi, N. K., & Mishra, N. (2015). Seasonal prediction of ISMR and relationship with EL–NINO and IOD in ECMWF system 4 coupled model. *Climate Change*, **1(4)**, 447–455.

37. Chaudhuri S., S. Goswami, Debanjana Das and A. Middey (2014) Meta-heuristic ant colony optimization technique to forecast the amount of summer monsoon rainfall: skill comparison with Markov chain model, Theor Appl Climatol (Springer), 116, 3-4, 585-595 (IF: 2.433) (CI 5).

38. Chaudhuri S. and J. Pal (2014) Cloud - Aerosol coupled index in estimating the break phase of Indian Summer Monsoon, Theor Appl Climatol (Springer), 118, 3, 447-464 (IF: 2.433).

39. Chaudhuri S. and J. Pal (2014), The influence of El Niño on the Indian summer monsoon rainfall anomaly: A diagnostic study of the '82/83 and '97/98 events, Meteor. Atmos. Phys.(Springer), 124, 3-4, 183-194 (IF: 1.172).

40. Pal J., S. Chaudhuri*, S. Guhathakurta (2015) The influence of galactic cosmic ray on all India annual rainfall and temperature, Adv. Space Res. (Elsevier), 55, 4, 1158-1167 (IF: 1.409) (CI 1).

41. J. Pal, S. Chaudhuri*, S. Mukherjee and A. Roy Chowdhury (2016) Probing for suitable climatology to estimate the predictability of Monsoon Onset over Kerala (MOK), India, Theor. Appl. Climatol. (Springer), (online first July 2016) DOI 10.1007/s00704-016-1868-9 (IF: 2.433).

42. Chaudhuri S, D. Das, S. Goswami and S.K. Das (2016) Long-range forecast of all India Summer Monsoon Rainfall using adaptive neuro-fuzzy inference system: skill comparison with CFSv2 model simulation and real - time forecast for the year 2015, Climate Dyn. (Springer), DOI 10.1007/s00382-016-3028-4 (online).

43. Nirupam Karmakar, Arindam Chakraborty and Ravi S Nanjundiah, 2016: Space-Time Evolution of the Low- and High-Frequency Intraseasonal Modes of the Indian Summer Monsoon., Mon. Wea. Rev., doi: 10.1175/MWR-D-16-0075.1.

44. An assessment of Indian monsoon seasonal forecasts and mechanisms underlying monsoon inter-annual variability in the Met Office GloSea5-GC2 system. S. J. Johnson,

A. G. Turner, S. J. Woolnough, G. M. Martin and C. MacLachlan. Climate Dynamics, published online 24 June 2016.

45. The resolution sensitivity of the South Asian monsoon and Indo-Pacific in a global 0.35° AGCM. S. J. Johnson*, R. C. Levine, A. G. Turner, G. M. Martin, S. J. Woolnough, R. Schiemann, M. S. Mizielinski, M. J. Roberts, P. L. Vidale, M.-E. Demory and J. Strachan (2016). Climate Dynamics, 46(3): 807-831. [*Note that S. J. Johnson was formerly known as S. J. Bush]

46. The effect of increased convective entrainment on Asian monsoon biases in the MetUM General Circulation Model. Bush, S. J., A. G. Turner, S. J. Woolnough, Gill M. Martin and N. P. Klingaman (2015) Quarterly Journal of the Royal Meteorological Society, 141: 311-326, January 2015

47. Wang, W., M.-P. Hung, S. J. Weaver, A. Kumar,and X. Fu, 2014: MJO prediction in the NCEP Climate Forecast System version 2. Clim. Dyn., DOI 10.1007/s00382-013-1806-9

48. Liu, R., and W. Wang, 2014: Multi-week prediction of South-East Asia rainfall variability during boreal summer in CFSv2. Clim. Dyn., 45, 493-509. DOI 10.1007/s00382-014-2401-4.

49. Wang, W., A. Kumar, X. Fu, 2015: How important is the sea surface temperature uncertainty in the prediction of tropical convection associated with the MJO? Mon. Wea. Rev., 143, 3156-3175. DOI: 10.1175/MWR-D-14-00385.1.

50. Lee, S.-S., B. Wang, D. E. Waliser, J. M. Neena, and J.-Y. Lee (2015), Predictability and prediction skill of the boreal summer intraseasonal oscillation in the Intraseasonal Variability Hindcast Experiment, J. Climate, DOI 10.1007/s00382-014-2461-5.

51. Neena, J. M., D. E. Walise, and X. Jiang (2016), Model Performance Metrics and Process Diagnostics for Boreal Summer Intraseasonal Variability, Climate Dynamics, In Press.

52. Guan, B., and D. E. Waliser (2015), Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies, Journal of Geophysical Research, 120, 12,514–512,535.

53. Li, J.-L. F., W.-L. Lee, D. Waliser, Y.-H. Wang, J.-Y. Yu, X. Jiang, T. L'Ecuyer, Y.-C. Chen, T. Kubar, E. Fetzer, and M. Mahakur (2016), Considering the radiative effects of snow on tropicalPacific Ocean radiative heating profiles in contemporary GCMs using A-Train observations, J. Geophys. Res., Atmos., 121, doi:10.1002/2015JD023587.

54. Cesana, G., D. E. Waliser, X. Jiang, and J.-L. F. Li (2015), Multi-model evaluation of cloud phase transition using satellite and reanalysis data, J. Geophys. Res. - Atmos., 120, doi:10.1002/2014JD022932.

55. Sluka, T., S. Penny, E. Kalnay, and T.Miyoshi, 2016: Assimilating atmospheric observations into the ocean using strongly coupled ensemble data assimilation. GRL, DOI: 10.1002/2015GL067238

56. Bombardi, R., E. K. Schneider, L. Marx, S. Halder, B. Singh, A. B. Tawfik, P. A. Dirmeyer, J. L. Kinter III, 2015: Improvements in the representation of the Indian Summer Monsoon in the NCEP Climate Forecast System version 2. Climate Dyn. (online) doi 10.1007/s00382-015-2484-6.

57. Bombardi, R. J., A. B. Tawfik. L. Marx; C.-S. Shin; E. K Schneider; P. A. Dirmeyer; J. L. Kinter III, 2016: The Heated Condensation Framework as a Convective Trigger in the NCEP Climate Forecast System version 2. J. Adv. Mod. Earth Sys., doi: 10.1002/2016MS000668.

58. Bombardi, R. J., A. B. Tawfik, L. Marx, C.-S. Shin, E. K. Schneider, P. A. Dirmeyer, J. L. Kinter, 2016: The Heated Condensation Framework as a Convective Trigger in the NCEP Climate Forecast System version 2. Oral presentation, AMS Annual Meeting, New Orleans (January 10-14, 2016)

59. Bombardi, R. J., A. B. Tawfik, L. Marx, C.-S. Shin, E. K. Schneider, P. A. Dirmeyer, J. L. Kinter, 2015: Implementing a New Convective Trigger function in the NCEP Climate Forecast System version 2. Poster presentation, CLIVAR Workshop, GFDL, New Jersey (October 15-16, 2015)

60. Dirmeyer, P. A., and S. Halder, 2016a: Application of the land-atmosphere coupling paradigm to the operational Coupled Forecast System (CFSv2). J. Hydrometeor. (submitted).

61. Dirmeyer, P. A., and S. Halder, 2016b: Sensitivity of surface fluxes and atmospheric boundary layer properties to initial soil moisture variations in CFSv2. Wea. Fcst. (submitted).

62. Dirmeyer, P. A., J. Wu, H. E. Norton, W. A. Dorigo, S. M. Quiring, T. W. Ford, J. A. Santanello Jr., M. G. Bosilovich, M. B. Ek, R. D. Koster, G. Balsamo, and D. M. Lawrence, 2016: Confronting weather and climate models with observational data from soil moisture networks over the United States. J. Hydrometeor., 17, 1049-1067, doi: 10.1175/JHM-D-15-0196.1.

63. Halder, S., and P. A. Dirmeyer, 2016: Relation of Eurasian snow cover and Indian summer monsoon rainfall: Importance of the delayed hydrological effect. J. Climate (submitted).

64. Halder, S., P. A. Dirmeyer, S. K. Saha, 2015: Uncertainty in the mean and variability of Indian summer monsoon due to land-atmosphere feedback in RegCM4. J. Geophys. Res., 120, 9437-9458, doi: 10.1002/2015JD023101.

65. Halder, S., S. K. Saha, P. A. Dirmeyer, T. N. Chase, and B. N. Goswami, 2016: Investigating the impact of land-use land-cover change on Indian summer monsoon daily rainfall and temperature during 1951-2005 using a regional climate model., Hydrol. Earth Sys. Sci., (accepted), doi: 10.5194/hessd-12-6575-2015.

66. Roxy, M.K. Rikita, P. Terray, S. Masson, 2014: The curious case of Indian Ocean Warming. Journal of Climate, Vol. 27, 8501-8508, doi:10.1175/JCLI-D-14-00471.1

67. Prodhomme, C., P. Terray, S. Masson, G. Boschat, T. Izumo, 2015: Oceanic factors controlling the Indian Summer Monsoon Onset in a coupled model. Climate Dynamics, Vol. 44, 977-1002, doi:10.1007/s00382-014-2200-y.

68. Roxy M. K., K. Ritika, P. Terray, R. Murutugudde, K. Ashok and B. N. Goswami, 2015: Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. Nature Communications, Vol. 6:7423, doi: 10.1038/ncomms8423 .

69. Roxy M. K., K. Ritika, P. Terray, S. Masson, 2015: Indian Ocean warming—the bigger picture. Bulletin of the American Meteorological Society, Vol. 96, 7, 1070-1071.

70. Terray P., S. Masson, C. Prodhomme, M. K. Roxy, K. P. Sooraj, 2016: Impacts of Indian and Atlantic oceans on ENSO in a comprehensive modeling framework. Climate Dynamics, Vol. 46, 2507-2533, doi:10.1007/s00382-015-2715-x

71. Samson, G., S. Masson, F. Durand, P. Terray, S. Berthet, S. Jullien, 2016: Role of land surface albedo and horizontal resolution on the Indian Summer Monsoon biases in a coupled ocean-atmosphere tropical-channel model. Climate dynamics, doi:10.1007/s00382-016-3161-0.

72. Roxy M.K., A. Modi, R. Murutugudde, V. Valsala, S. Panickal, S. Prasanna Kumar, M. Ravichandran, M. Vichi and M. Levy, 2016: A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean. Geophys. Res. Lett., 43, 826-833, doi:10.1002/2015gl066979

73. Narapusetty, B., Murtugudde, R., Wang, H., and A. Kumar, 2015: Ocean-atmosphere processes driving Indian Summer Monsoon biases in CFSv2 hindcasts., Clim. Dyn. doi: 10.1007/s00382-015-2910-9

74. Wang, H., Murtugudde, R., and A. Kumar, 2016: Evolution of Indian Ocean dipole and its forcing mechanisms in the absence of ENSO, Clim. Dyn. doi: doi:10.1007/s00382-016-2977-y

75. Xi, J., L. Zhou, R. Murtugudde, and L. Jiang, 2014: Impacts of intraseasonal SST anomalies on precipitation during Indian summer monsoon, J. Clim., 28, 4561–4575.

76. Vijay, P., M. S. Girishkumar, M. Ravichandran, and R. Murtugudde, 2013: Influence of the Atlantic Zonal mode on monsoon depression in the Bay of Bengal during June-August. J. Geophys. Res., 119, 6456-6469. DOI:10.1002/2014JD021494

77. Vijay, P., M. S. Girishkumar, S. Sivareddy, M. Ravichandran and R. Mur-tugudde, 2014: Relation between the upper ocean heat content in the equatorial Atlantic during boreal spring and the Indian summer monsoon rainfall during June-September. sub judice, Int. J. Clim.

78. Vittal, H., S. Ghosh, S. Karmakar, and R. Murtugudde, 2016: Revisiting the Dependence of Precipitation Extremes on Temperature with the Observed Long-term Dataset over India. Sci. Rep., DOI:10.1038/srep31039

79. Ravi Kumar, K., V. Valsala, J. V. Revadekar, P. Pillai, S. Chakraborty, and R. Murtugudde, 2016: Intra-seasonal variability of atmospheric CO2 concentrations over India during Summer Monsoons. Atm. Environ., 142, 229-237. doi:10.1016/j.atmosenv.2016.07.023

80. Zhou, L., R. Murtugudde, D. Chen and Y. Tang, 2016: A Central Indian Ocean Mode and Heavy Precipitation during Indian Summer Monsoon. Revised, J. Clim.

81. Zhou, L., R. Murtugudde, D. Chen and Y. Tang, 2016: Seasonal and Interannual Variabilities of the Central Indian Ocean Mode. Submitted, J. Clim.

82. Sabeerali, C. T., S. A. Rao, G. George, D. N. Rao, S. Mahapatra, A. Kulkarni, and R. Murtugude, 2014: Modulation of monsoon intra-seasonal oscillations in the recent warming period. J. Geophys. Res., 119, 5185-5203. DOI:10.1002/2013JD021261

83. Ravi Kumar, K., Y. Tiwari, V. Valsala and R. Murtugudde, 2014: On understanding of land-ocean CO2 contrast over Bay of Bengal: A case study during 2009 summer monsoon season. Environ. Sci. Poll. Res., 21, 5066-75DOI: 10.1007/s11356-013-2386-2.

84. Zhou, L., and R. Murtugudde, 2014: Impact of northward propagating intraseasonal variability on the onset of Indian summer monsoon. J. Clim., 27, 126-139. doi: http://dx.doi.org/10.1175/JCLI-D-13-00214.1

85. Das, S., D. Sengupta, A. Chakraborty, J. Sukhatme, and R. Murtugudde, 2014: Low-frequency intraseasonal variability in a zonally symmetric aquaplanet model. sub judice, Clim. Dyn.

86. Goswami, B. B., M. Deshpande, P. Mukhopadhyay, S. K. Saha, A. Surya Chandra Rao, R. Murthugudde, and B. N. Goswami, 2014: Identifying the source of Indian summer monsoon bias in NCEP CFSv2. Clim. Dyn., DOI:10.1007/s00382-014-2089-5.

87. Shashikanth, K., S. Ghosh, C. G. Madhusoodan, T. I. Eldho, K. Rajendran, and R. Murtugudde, 2014: Comparing Statistically Downscaled Simulations of Indian Monsoon at different spatial Resolutions. J. Hydrology, DOI: 10.1016/j.jhydrol.2014.10.042.

88. Mathew, K. R., R. Kapoor, P. Terray, R. Murtugudde, K. Ashok, and B. N. Goswami, 2014: Warm Indian Ocean, Weak Asian Monsoon. Nature Commun. , 6:7423, doi:10.1038/ncomms8423

89. T. N. Krishnamurti, V. Kumar, A. Simon, A. Thomas, A. Bhardwaj and Sweta Das, 2016: March of buoyancy elements during extreme rainfall over India: Climate Dynamics, DOI 10.1007/s00382-016-3183-7

90. T. N. Krishnamurti, S. Dubey, V. Kumar, D. Linoj, and A. Bhardwaj, 2016: Scale interaction and the flood event over south India. Under review in Quat. J. Roy Met Soc.

91. T. N. Krishnamurti and V. Kumar: Buoyancy streams along hurricane rainbands, cloud flare up in the eye wall and rapid intensification of hurricane Ingrid. Submitted to Monthly Weather review 2016.

92. Kumar, V., and T. N. Krishnamurti, (2015): Mesoscale modeling for the rapid movement of monsoonal isochrones, Atmospheric Science Letters, 17, 78-86.

93. Krishnamurti, T. N. and Sanjay, J. 2003.A New Approach to the cumulus parameterization issue. Tellus 55A, 275–300.

94. S. Dubey, T. N. Krishnamurti and V. Kumar: On the Scale Interactions between the MJO and Synoptic Scale. Submitted to Monthly Weather review 2016.

95. Li Y., W. Han, W. Wang, and M. Ravichandran, 2016: Intraseasonal Variability of SST and Precipitation in the Arabian Sea during Indian Summer Monsoon: Impact of Ocean Mixed Layer Depth. J. Clim., DOI: http://dx.doi.org/10.1175/JCLI-D-16-0238.1.

96. Prakash, K.R. & Pant, V. (2017), Upper oceanic response to tropical cyclone Phailin in the Bay of Bengal using a coupled atmosphere-ocean model, Ocean Dynamics, 67: 51. doi:10.1007/s10236-016-1020-5.

(C) Accepted/Under Review/ Communicated papers (through National and International Projects of Monsoon Mission):

97. Shahi, N. K., Rai, S., Sahai, A. K., Abhilash, S. “South Asian monsoon variability on intraseasonal time scale in the latest version of NCEP CFS”. (Manuscript under preparation)

98. Pal J., S. Chaudhuri*, A. Roy Chowdhury and D. Basu (2016) An Investigation on the influence of Southern Annular Mode on Indian Summer Monsoon Rainfall, Meteorol Appl (accepted – in press) (IF: 1.273).

99. C. T. Sabeerali, R. S. Ajayamohan, D. Giannakis and Andrew J Majda (2016) Extraction and prediction of monsoon intraseasonal oscillations: An approach based on nonlinear Laplacian spectral analysis., Climate Dynamics (under review) .

100. Nan Chen, Andrew J Majda, C. T. Sabeerali and R. S. Ajayamohan (2016) Predicting the intraseasonal precipitation monsoon indices through a low-order nonlinear stochastic model (Manuscript in final stage to submit)

101. R. Alexander, Z. Zhao, E. Szekely, and D. Giannakis (2016), “Kernel Analog Forecasting of Intraseasonal Oscillations”, J. Atmos. Sci., in revision

102. Boreal summer sub-seasonal variability of the South Asian monsoon in the Met Office GloSea5 initialized coupled model. A. Jayakumar, A. G. Turner, S. J. Johnson, E. N. Rajagopal, Saji Mohandas and A. K. Mitra. Climate Dynamics, submitted December 2015, revised version with minor corrections submitted August 2016.

103. S. Mohan and H. Annamalai, 2016: Extended monsoon episodes over South Asia – assessing thermodynamic processes in reanalysis ensemble (Climate Dynamics – submitted)

104. S. Mohan, H. Annamalai et al. 2016: Extended monsoon episodes over South Asia: Representation of atmospheric and oceanic processes in CFSv2 (currently going through internal review)

105. H. Annamalai et al. 2016: Extended break conditions during monsoon onset phase: distinct thermodynamical processes and their representation in CFSv2 (in preparation)

106. H. Annamalai, 2016: Severe limitations in reanalysis-based diagnostics of processes over the monsoon region – a proposal for in-situ observations (in preparation).

107. Ge, Xuyang, W. Wang, A. Kumar, Y. Zhang, 2016: Simulations of SST diurnal and intraseasonal variability in an oceanic general circulation model. (Submitted to Clim. Dyn.).

108. Kim, Waliser, Cesana, Jiang, L’Ecuyer, and Mani (2016), Radiative Heating And Cloud-water Vertical Profiles Associated With Boreal Summer Intra-seasonal Oscillation, Geophys. Res. Let., (To be Submitted).

109. Bombardi, R. J., K. V. Pegion, J. L. Kinter, B. A. Cash, J. M. Adams, 2016: Sub-seasonal predictability of the onset and demise of the rainy season over monsoonal regions. Frontiers Atmos. Sci. (submitted).

110. Cretat, J., P. Terray, S. Masson, P.V. Sooraj, M. K. Roxy, 2016 : Indian Ocean and Indian Summer Monsoon : relationships without ENSO in ocean-atmosphere coupled simulations. Revised for Climate Dynamics.

111. Terray P., P.V. Sooraj, S. Masson, R.P.M. Krishna, G. Samson, A.G. Prajeesh, 2016 : Towards a realistic simulation of boreal summer tropical rainfall climatology in state-of-the art climate coupled models. Revised for Nature Communications.

112. Krishnamurti, T. N. , S. Jana, R. Krishnamurti, Vinay Kumar, R. Deepa, F. Pappa, M. Bourassa and M. Ali , “Monsoonal Intra-seasonal Oscillations in the Ocean Heat Content

over the Surface Layers of the Bay of Bengal” submitted in Journal of Marine Systems Science.

113. Krishnamurti R. ,and T. N. Krishnamurti, “Deep Boundary Layers in Source-Sink Driven Flows on a Rotating Beta Plane” , is under revision for publication in the Journal of Fluid Mechanics.

114. Noska, R. and V. Misra, 2016: Characterizing the onset and demise of the Indian Summer Monsoon. Geophys. Res. Lett., doi:10.1002/2016GL068409. In press.

115. Misra, V., A. Mishra, and A. Bhardwaj, 2016: High resolution regional coupled ocean-atmosphere simulation of the Indian summer monsoon. Clim. Dyn., in review.

116. Misra, V., A. Bhardwaj, and R. Noska, 2016: Understanding the variations of the length and seasonal rainfall anomalies of the Indian summer monsoon. J. Clim., in review.

117. Russell, H. G. and V. Misra, 2016: Ice versus liquid water saturation in simulations of the Indian summer monsoon. Clim. Dyn., in review.

118. Mishra, A. and V. Misra, 2016: The impact of coupled ocean-atmosphere interactions on downscaling of the Indian summer monsoon (in preparation).

119. Misra, V., R. Noska, A. Bhardwaj, and A. Mishra, 2016: Local onset and demise of the Indian summer monsoon(in preparation).

120. Srinivasu, U., M. Ravichandran,Weiqing Han, S.Sivareddy, H Rahman, Yuanlong Li and Shailesh Nayak, 2016: Causes for decadal reversal of North Indian Ocean sea level in recent two decades. Clim. Dyn., revised.

121. Li Y., W. Han, W. Wang, M. Ravichandran, and T. Shinoda, 2016a: Barrier Layer and Monsoon Intra-seasonal Oscillations (MISOs), Part I: Causes for intra-seasonal-to-inter-annual variability of barrier layer over the Indian Ocean. JGR-Oceans, Manuscript in preparation.

122. Li Y., W. Han, W. Wang, M. Ravichandran, and T. Shinoda, 2016b: Barrier Layer and Monsoon Intra-seasonal Oscillations (MISOs), Part II: Effects of the Bay of Bengal barrier layer on SST and MISOs. JGR-Oceans, Manuscript in preparation.

123. Dheeraj Varma and Manikandan Mathur (2016), Internal wave resonant triads in finite-depthnonuniform stratifications, J. Fluid Mech., in review.

124. Arnold L. Gordon, Emily Shroyer, V.S.N. Murty (2016) An Intra-thermocline Eddy and atropical cyclone in the Bay of Bengal. Submitted to Nature Communications.

(D) Papers in Symposium/Workshops etc.:

125. Bombardi, R. J., E. K. Schneider, L. Marx, S. Halder, B. Singh, A. B. Tawfik, P. A. Dirmeyer, and J. L. Kinter III, 2014: Sensitivity of Indian Summer Monsoon Rainfall Simulation to Convection Parameterizations and Convective Trigger Functions. National Monsoon Mission Workshop, Pune, India, February 2014.

126. Bombardi, R. J., E. K. Schneider, L. Marx, S. Halder, B. Singh, A. B. Tawfik, P. A. Dirmeyer, J. L. Kinter, 2014: Improvements in the representation of the Indian Summer Monsoon in the NCEP Climate Forecast System version 2. Oral presentation, AGU Fall Meeting, San Francisco (December 15-19, 2014).

127. Das D, S. Chaudhuri, Zaiyu Wang (2015) Ambiguity in predictability of Summer Monsoon in various climate models, Climate Dyn. (Springer), (status: 1st revision submitted)(IF:4.708).

128. Roy Chowdhury A., S. Chaudhuri*, D. Das and S. Maitra (2015) Bias Estimation for Indian Summer Monsoon with UK Met Office Unified Model, Climate Dyn. (status: 1st revision submitted)(IF:4.708).

129. Chaudhuri S.*, D. Das, F. Khan, J. Pal, A. Roy Chowdhury, I. Sarkar (2016) Variability in the onset of summer monsoon over Gangetic West Bengal, India: An investigation with climatology of tropopause characteristics, Int J. Climatol (Status: 1st Revision submitted) (IF:3.609).

130. Das D, S. Chaudhuri*, A. Roy Chowdhury (2016) Simulation of synoptic features during summer monsoon onset over GWB, India with CFSv2 coupled model: skill and bias assessment, Climate Dyn. (Springer), (status: 2nd revision submitted)(IF:4.708)

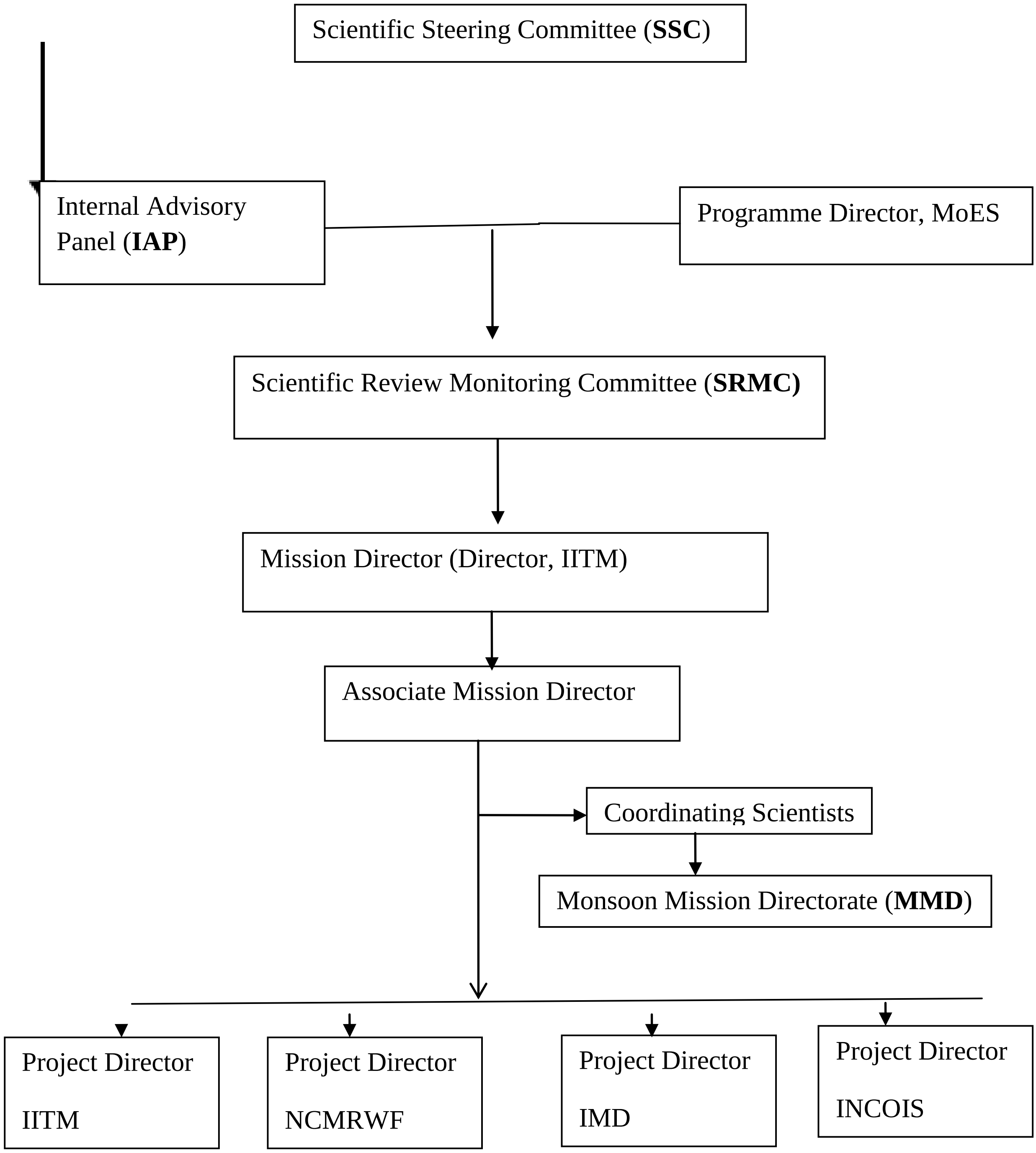
(E) PhD Degree awarded

1) Goswami, B.B (2014): Study of Indian Summer Monsoon Intraseasonal Oscillation in Multiscale Modelling Framework. (Pune university)
2) Halder Madhuparna (2014). Study of Cloud Microphysics and lightning Activity using observations and Numerical Modelling. (Pune University)
3) Sabeerali CT (2014): Modulation of Monsoon Intra-Seasonal Oscillations by Global Warming. (Pune University)
4) **Santra Abhik (2015) :** Impact of cloud Processes on Tropical Intraseasonal oscillation: Numerical Modeling Studies (pune university)
5) **Chakravorty S (2015):** Understanding the Basin scale Interannual warming of the Indian Ocean and its regional Impacts (Pune University)
6) **Sur Sharmila (2015).** Studies on the Characteristics of Intraseasonal Oscillations during Extreme Monsoon Years. (Pune University)
7) **Rahul S (2015):** A Model Study on the Indian Ocean Warming and associated processes (Pune University)

8) **Borah Nabnitha (2015):** Extended Range Prediction of Indian Summer Monsoon: Development of a Non-Linear Technique and Bias Correction of Dynamical Model Forecast. (Pune University)
9) **Gibies George (2016) .** Role of Ocean-Atmosphere Coupling in the Seasonal Prediction of South Asia Monsoon. (Pune University).
10) **Nagarjuna Rao (2017)** Interactions between the Synoptic Variability and the Seasonal Mean Monsoon: Role of Ocean-Atmosphere Coupling (Pune University).

Annexure-2

Working Structure of the Monsoon Mission:



Scientific Steering Committee (SSC)

1. **Dr. M Rajeevan**, Secretary, ESSO-MoES Chairman
2. **Prof. J. Sreenivasan**, CAOS, IISc., Bangalore Co-Chair
3. Chairperson, SRMC Member
4. **Prof. R. S. Nunjundiah**, Monsoon Mission Director Member
5. **Dr. K. J. Ramesh**, Director General, ESSO-IMD Member
6. **Dr. E. N. Rajagopal**, Director, ESSO-NCMRWF Member
7. **Dr. Parvinder Maini**, Program Director, ESSO-MoES Member Convener

Scientific Review and Monitoring Committee (SRMC)

1. **Prof. B. N. Goswami** Chairperson
2. **Shri. D. R. Sikka**, New Delhi Member
3. **Prof. U. C. Mohanty**, IIT Bhubaneswar Member
4. **Dr. Ajit Tyagi**, ESSO - MoES Member
5. **Dr. C. M. Kishtwal**, SAC, Ahmedabad Member
6. **Prof. G. S. Bhat**, CAOS, IISc., Bangalore Member
7. **Prof. Debasis Sengupta**, IISc., Bangalore Member
8. **Dr. K. Krishnamoorthy**, ISRO, Bangalore Member
9. **Dr. K. J. Ramesh**, Director General, ESSO-IMD Member
10. **Prof. R. S. Nunjundiah**, Director, IITM (Mission Director) Member
11. **Dr. R. Krishnan**, Executive Director, CCCRMember
12. **Dr. Y. V. N. Krishnamurty,** Director, NRSC, Hyderabad Member
13. **Dr. E. N. Rajagopal**, Director, ESSO-NCMRWF, Noida Member
14. **Dr. Satheesh Shenoi**, Director, ESSO-INCOIS, Hyderabad Member
15. **Dr. Parvinder Maini**, Program Director, ESSO-MoES Member
16. **All Project Directors** : **Dr. A. K. Mitra** of ESSO-NCMRWF; [Permanent Invitee]
17. **Dr. S. K. RoyBhowmick** of ESSO-IMD; [Permanent Invitee]
18. **Dr. D. S. Pai** of ESSO-IMD; [Permanent Invitee]
19. **Dr. P. A. Francis** of ESSO-INCOIS) [Permanent Invitee] , and
20. **Dr. A. Suryachandra Rao,** Scientist-F, ESSO-IITM Member Convener

Monsoon Mission Directorate (MMD):

1. **Prof. R. S. Nunjundiah,** Director, ESSO-IITM & Mission Director
2. **Dr. A. Suryachandra Rao,** Scientist-F, ESSO-IITM & Associate Mission Director
3. **Mr. Somnath Mahapatra,** Scientist-E, ESSO-IITM & Coordinating Scientist
4. **Dr. Prasanth A. Pillai,** Scientist-D, ESSO-IITM & Coordinating Scientist
5. **Dr. R. S. Maheshkumar,** Scientist-D, ESSO-IITM & Coordinating Scientist
6. **Mr. D. A. Ramu**, Scientist-C, ESSO-IITM & Coordinating Scientist
7. **Mr. Anil Kumar Pandey,** Project Computer Scientist
8. **Dr. Gibies George,** Project Scientist,Monsoon Missionprogram
9. **Mr. Harikishan Gandham,** Project Scientist,Monsoon Missionprogram
10. **Mr. Krunal D. Kamble,** UDC,Monsoon Mission Directorate

11.Mr. Vikas D. Dhindle, UDC,Monsoon Mission Directorate.

❖ Deputation of MoES Scientists under Monsoon Mission :

During last 3 years, 10 MoES Scientists (5 from ESSO-IITM, 3 from ESSO-INCOIS and 2 from ESSO-NCMRWF) have been deputed abroad to get training and to work with Principal Investigators (world renowned scientists) of some International projects of the Monsoon Mission. For their deputations, funds were provided mainly from Monsoon Mission funds.

List of MoES Scientists deputed under Monsoon Mission :

Sr. No.	Name of Scientist	Organization	Deputed to
1	Dr. A. Jayakumar, Sc-C	NCMRWF, Noida	University of Reading, UK
2	Dr. Indira Rani S.,	NCMRWF, Noida	MET Office, UK and ECMWF
3	Mr. S. Sivareddy, Sc-B	INCOIS, Hyderabad	University of Maryland, USA
4	Dr. Arya Paul, Sc-C	INCOIS, Hyderabad	University of Maryland, USA
5	Mr. Mata Mahankur, Sc-C	IITM, Pune	University of California, USA
6	Dr. S. Abhilash	IITM, Pune	University of Miami, USA
7	Dr. Pani Murali Krishna, Sc-D	IITM, Pune	University of Victoria, Canada
8	Dr. Sreenivas Pentakota, Sc-D	IITM, Pune	University of Maryland, USA
9	Mr. G. Prajeesh, Sc-C	IITM, Pune	USA
10	Dr. Girishkumar	INCOIS, Hyderabad	FSU, USA (with Dr. Ruby Krishnamurti)

There have been lot of benefits from these deputations for research & development in the field of Atmospheric & ocean sciences, both on weather and climate time scales. Some of the important achievements during last 3 years (as an outcome of these deputations) are as follows:

- Development and implementation of a coupled ocean-atmosphere data assimilation system, based on Local Ensemble Transform Kalman Filter (**LETKF**) technique for the Climate Forecast System (**CFS**) model. This coupled CFS LETKF data assimilation system will be very useful for operational monsoon prediction activities at IITM & IMD, beneficial for the whole country.
- Help and support in development of Extended range prediction system for predicting active and break spells (**ERPAS**) of Indian summer monsoon rainfall, with significant prediction skill.
- With an aim to improve the CFSv2 model, one scientist have learnt about the Stochastic model. **The Stochastic model has been implemented in CFSv2**, by replacing the default convective parameterizations and was run on the Cluster Aditya (HPCS) at IITM, Pune. Now we have the Stochastic model at IITM, which gives a good MJO and a better propagation of Kelvin waves, resulting better prediction skill.

- **2C-ICE (**Combined radar and lidar ice-cloud products) and **DARDAR** (another raDAR & liDAR combined products for ice cloud) satellite data products have been retrieved and analysed using advanced algorithms and variational techniques of data assimilation.

- Help and support in development of Earth System model (**ESM**) at CCCR, IITM, Pune.

- A major benefit of these visits is the development of strong scientific and technical capability in India in the areas of atmosphere-ocean coupled modelling which is essential for advancing the skill of forecasting weather and climate, including monsoon rainfall over South Asia.

Major Achievements of the Monsoon Mission: Report

Compiled by

Somnath Mahapatra, Prasanth A Pillai and Suryachandra A. Rao

ESSO – Indian Institute of Tropical Meteorology, Pune

The Earth System Sciences Organization (ESSO)
Ministry of Earth Sciences (MoES), Government of India

October, 2017