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Special Issue on

India's Monsoon Mission

WCRP
World Climate Research Programme

World Meteorological Organization
United Nations Educational, Scientific and Cultural Organization
Intergovernmental Oceanographic Commission
International Science Council

CLIVAR (Climate and Ocean - Variability, Predictability, and Change) is the World Climate Research Programme's core project on the Ocean-Atmosphere System

India’s Monsoon Mission: Editorial

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The Monsoons have always been a focus of great interest to CLIVAR, and this was further enhanced in 2015 when there was a reorganization of monsoon research efforts within the World Climate Research Programme (WCRP). Prior to 2015, CLIVAR used to have three separate regional panels on the topic, each focused on a specific geographical area dominated by monsoons: the Americas, Africa, and the Asian-Australian region. However, it has been recognized that the monsoons around the globe have many common elements and that overall progress in our scientific understanding of the monsoons would benefit from an active interaction of individuals and groups that study these various regional monsoons. Furthermore, the efforts of the Global Water and Energy Exchanges (GEWEX) project of the WCRP are highly relevant to the terrestrial and hydro-thermodynamic aspects of monsoons. As a result, a single Monsoons Panel spanning both CLIVAR and GEWEX was formed with membership drawn from both communities. To highlight this milestone, a special issue of the CLIVAR Exchanges magazine focusing on the monsoons was produced (see http://clivar.org/documents/exchanges-66). At the same time, the International CLIVAR Monsoon Project Office (ICMPO) was established at the Indian Institute of Tropical Meteorology (IITM) of the Ministry of Earth Sciences under an agreement between WCRP and IITM approved by the Government of India. ICMPO has since been providing dedicated support to the activities of the Monsoons Panel.

Much progress has been made during these last five years and thus we believe it is very timely that the Monsoons Panel, with active support by the ICMPO, coordinates the production of two publications: one CLIVAR Exchanges special issue (focusing on the India’s Monsoon Mission) and one GEWEX Quarterly special issue (focusing on global aspects of the Monsoon System).

India is blessed with two monsoons, Southwest monsoon during June to September and Northeast monsoon during October-December. Monsoons affect the Indian people in every aspect of their lives. From ancient history to modern times, it has controlled their everyday existence. Adequate and timely monsoon rains is very crucial for providing drinking water, farming operations, water resources (reservoir) management, generation of hydro power etc. Monsoon variability even influences the country’s economy. A severe monsoon drought can pull down India’s GDP even up to 2%. Indeed, the Indian summer monsoon was the target of the very first science-based seasonal forecast in the world, with the attempt by Blanford (1884)[1] to forecast monsoon rainfall based on the hypothesis that “varying extent and thickness of the Himalayan snows exercise a great and prolonged influence on the climate conditions and weather of the plains of northwest India”. Thus, the importance of monsoon prediction for socio-economic applications was recognized quite early but understanding its variability across a wide range of time and space scales and providing reliable predictions remains a challenge even today, despite many scientific and technological advances. Recognizing the urgent need for improving monsoon prediction capabilities in the country in a systematic and timely manner, the Government of India had launched an ambitious and well-resourced research programme on Mission mode, called the Monsoon Mission. The first phase of the mission was implemented during 2012-2017 and the second phase which started in 2017 is underway. Through this mission, India also augmented its capability of High-Performance Computing (HPC), which is close to 10 petaflops now.

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[1] Blanford, H.F., 1884: On the connection of Himalayan snowfall and seasons of drought in India. *Proc. R. Soc. London*, 37, 3-22.

The main objective of the Monsoon Mission was to improve monsoon forecasts in all time scales, right from short-range to seasonal. By recognizing the massive quantum of work involved in improving monsoon forecasts, the Indian Government decided to adopt a mission mode approach to mobilize and motivate technical expertise from scientists working in academic and research institutes from India and abroad in a well-coordinated manner. There was an excellent response from the academic community. In total, 30 research projects were sanctioned during the first phase and 20 projects in the second phase. The most important milestone under the Monsoon Mission was implementing the state-of-the-art dynamical prediction systems on all time scales, from short range to seasonal. India is now proud of having one of the best weather and climate prediction systems for generating real time forecasts and warnings. The second phase of the mission focuses on applications and prediction of extremes.

A unique feature of India's Monsoon Mission is that, though fully funded from national resources, it has supported a significant number of international groups. This has helped to create a win-win situation, for the country to address its own priorities in collaboration with the international community, and the international community to gain access to resources to tackle some of the fundamental challenges in monsoon modelling which have implications for model fidelity even in other parts of the world. If this approach can be emulated by other countries, resource mobilization for international research programmes, including the WCRP, can be greatly facilitated.

In this special issue of the *CLIVAR Exchanges* featuring "India's Monsoon Mission", we have included articles discussing various aspects of the Monsoon Mission. A similar special issue of *GEWEX Quarterly* is also being brought out at the same time on the broader aspects of the monsoons around the world. This fits very well with the joining of forces by CLIVAR and GEWEX in coordinating monsoon research, through their joint Monsoons Panel.

This special issue includes an article on basic challenges in monsoon prediction (*Srinivasan*), the methodology and salient results from the Monsoon Mission (*Nanjundiah and Rao* and *Rao et al.*) and their contributions to operational advances in short to medium range, extended range and seasonal forecasts (*Mohapatra et al.*), various societal applications developed under the mission (*Sahai et al.*), innovative coupled data assimilation methods (*Da et al.*) and Stochastic Parameterization (*Khouider*). *Indira Rani et al.* discuss the new high resolution (12 km) regional reanalysis data set developed under the mission. *Turner* outlines a joint Indo-UK funding framework in association with the Monsoon Mission for three monsoon-focused field campaigns, while *Sengupta et al.* discuss the salient aspects of a field campaign conducted over the Bay of Bengal to study ocean mixing processes. *Srinivasan et al.* discuss the Monsoon Mission contributions to regional climate information and services for South Asia. *Krishnan et al.* discusses the south Asian Monsoon Climate Change projections made using the Earth System Model developed in India. These articles together provide insights into the Monsoon Mission and tell the success story in devoting concerted efforts to improve monsoon forecasts in India and derive socio-economic benefits.

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Monsoon Research:
Present Status and Future Prospects

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1. Introduction

The prediction of rainfall has been the main concern in tropics after the advent of agriculture. The long-range forecasting of the Indian summer monsoon rainfall was first attempted in the late 19th century after the droughts in India in 1877 and 1878. The initial attempts were based on snow cover over the Himalayas in the spring. Later, Sir Gilbert Walker, Director General of India Meteorological Department (IMD) from 1904 to 1924, developed a regression technique to relate the pressure fluctuations in the southern hemisphere in winter to the Indian summer monsoon rainfall. The methods proposed by Sir Gilbert Walker were however not accurate during 1921-1940 because there were no droughts during this period. The success of these regression/statistical methods was limited because it was found that factors that influence the Indian monsoon rainfall tend to change on decadal scales. Regression methods were good at predicting normal monsoon but could not predict droughts reliably (except for 2015). The regression methods were, however, able to predict the onset of monsoon over Kerala quite well (Pai and Rajeevan, 2009).

2. Present Status

After the advent of coupled ocean-atmosphere general circulation models there was an expectation that these models will be better than statistical methods for the prediction of seasonal rainfall, but this expectation has not been met so far. The presence of chaos makes the accurate prediction of seasonal rainfall a great challenge that can be partly overcome using ensemble mean. Weishemer and Palmer (2014) have argued that the forecast of seasonal rainfall over India can be marginally useful. Dynamical models are able to predict winds more accurately than rainfall. Hence some people have proposed a hybrid method. In this method, the general circulation models predict the wind and a statistical model correlates winds with rainfall. Pattanaik and Kumar (2015) have shown that the hybrid model increases the correlation coefficient by 50% when compared to the general circulation model for the prediction of Indian summer rainfall during the period 1982-2009.

The short term forecast of monsoon rainfall (up to 3-4 days) has improved dramatically in recent years on account of higher spatial resolution and assimilation of large amount of satellite data. The improvements in forecast that have occurred through projects undertaken in India's "Monsoon Mission" have been discussed in this special issue. There is an improvement in the prediction of transition from active to break monsoon (Pattanaik et al., 2020). In India, the evacuation of people based on accurate forecast of cyclone tracks has been demonstrated. Although the tracks of the cyclone are accurate, the same is not true for cyclone intensity. The prediction of monthly and seasonal monsoon rainfall has not been easy although the correlations have improved. The interannual variation of Indian monsoon rainfall is around 10% and hence predicting this variation is not easy. The root mean square error (RMSE) in the prediction of seasonal mean monsoon rainfall is very close to the observed interannual variation of monsoon rainfall in most climate models and IMD's statistical forecasting system. If the RMSE of the seasonal forecast is comparable to interannual standard deviation of observed rainfall, then the seasonal forecast is of limited value.

Hence one can argue that the seasonal prediction will be marginally useful. The forecast of seasonal mean rainfall has to be more accurate before it can be effectively used by policy makers. The improvement in seasonal forecasting will depend upon our understanding the dominant parameters that control monsoon rainfall based on heuristic models.

The impact of greenhouse gases on monsoon has been studied well in view of the concerns regarding the impact of global warming on monsoons. Most climate models predict that monsoon will increase on account of an increase in the amount of water vapor in the atmosphere and increase in rainfall in northern hemisphere will be more than that in the southern hemisphere. There is wide variation with regard to the amount of increase predicted by different models because the models indicate a different impact on circulation changes. The major discrepancies between different climate models occur on smaller spatial scales. For example, climate models with high spatial resolution indicate that an increase in carbon dioxide will increase rainfall over most of India but decrease it over Kerala (Rajendran et al.,2012). This feature is not seen in models with low resolution because they are not able to simulate accurately orographic rainfall over Kerala.

The impact of aerosols on short term forecast and long-term prediction of monsoon is not fully understood. This is because the spatial and temporal variation of aerosols is complex and not well documented and the radiative properties of dust, sulphate aerosols and soot are not well known. According to the land-sea contrast theory, the impact of aerosols is to cool the land surface and hence weaken the monsoon. This explanation is not appropriate when absorbing aerosols are present. These aerosols heat the atmosphere and cool the surface. Absorbing aerosols reduces the albedo of the earth-atmosphere system and hence increases the net radiation at the top of the atmosphere. The simulation of monsoon by atmospheric general circulation models indicate that the presence of soot will enhance the monsoon locally. The heating of the atmosphere by soot over India can induce reduction of monsoon rainfall in other regions of the world through changes in large-scale circulation.

3. Future prospects

The major paradigm for understanding the monsoon phenomenon has been the concept of land-sea contrast in surface temperature proposed by Halley in 1686. This paradigm has several fundamental flaws as highlighted by Gadgil (2018). An alternative paradigm based on the energetics of the atmosphere was proposed by Neelin and Held (1987). This approach considers the energy and moisture budget of an atmospheric column in the tropics. This approach shows that the moisture convergence over land (i.e., precipitation minus evaporation) is directly proportional to net radiative energy incident at the top of the atmosphere and inversely proportional to gross moist stability. The gross moist stability is a measure of the fraction of moist static energy exported out of the column per unit moisture imported into the column. According to the Neelin and Held (1987) hypothesis, the mass that can converge in the inter-tropical convergence zone (ITCZ) is constrained by the amount of energy available. During the summer boreal monsoon season the net radiation at the top of the atmosphere in Africa (north of 20° N) is small or negative and hence the ITCZ in Africa does not extend as far north as it does over India. Srinivasan (2001) has shown that a diagnostic model based on this hypothesis can simulate the seasonal variation of rainfall quite well. This paradigm has been used by Jalihal et al. (2019) to develop a diagnostic model that accounts for the centennial scale variation of the Indian summer monsoon simulated by a coupled ocean-atmosphere model during the past 22,000 years. This model demonstrates why the response of the monsoon to changes in incident solar radiation is different over land and ocean (Jalihal et al., 2020). The monsoon rainfall over land is linearly proportional to the net radiation incident at the top of the atmosphere while the rainfall over ocean is strongly dependent on the transfer of latent heat from the surface ocean to the atmosphere. This alternative paradigm can be expected to help to improve the forecast of the monsoon on a seasonal scale.

One can expect a steady improvement in the short term and medium term forecast of rainfall in the next decade on account of the use of ocean-atmosphere coupled general circulation models with spatial resolution around 1 km (Wedi et al., 2020). At this resolution the use of convection parametrization can be avoided. The assimilation of more data from satellites will reduce the error in the initial conditions. These models will demand the use of exa-scale (10^{18} floating operations per second) computing resources. There may be a need for developing better heuristic models to predict the 10-15 day and 30-60 day modes of rainfall variability.

In the past, an understanding of monsoon variability was limited by the fact that we did not have data on monsoon rainfall for more than 150 years. In recent years, the variability of the monsoon during the past 100,000 years has been inferred from proxy data. The variations in monsoon obtained from proxy data has been compared with simulation by climate models. This comparison has enriched our understanding of the various modes of monsoon variability and their linkage to global circulation anomalies. The insight obtained from these studies will be important to understand how monsoon will vary in the next hundred years on account of both natural variability and those induced by human actions. The increase in extreme rainfall events, during the past fifty years, has highlighted the need for more accurate forecast of these events in the future. Wang et al. (2015) have shown that the poor skill in seasonal forecasting is related to the inability to forecast the extremes in seasonal mean rainfall during the period 1989-2012. They argue that global warming has altered the parameters that influence the Indian monsoon. Many processes in the monsoon system are non-linear and hence exhibit threshold behavior. Hence one can expect that in the future there will be a greater use of Artificial intelligence (AI) and machine learning in monsoon research. In a recent paper, Ham et al. (2019) have shown that deep learning techniques can be used to forecast ENSO two years ahead. The use of deep learning techniques will be effective if a large amount of data can be used to train the system. Ham et al. (2019) used the data from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) to train the convolutional neural network (CNN). They argue that CNNs would be appropriate to reveal the links between three-dimensional predictor fields and the predictand index. A similar approach must be taken up for the prediction of monsoon rainfall. Li and Wang (2016) have advocated the use of physics based empirical models. They have shown that the temporal correlation skills of such models are more than twice that of dynamical models. The coupled ocean-atmosphere general circulation models tend to have a wet bias over the ocean and dry bias over land. The reduction of these biases will improve the skill of their prediction of rainfall. Recent work by Jalihal et al. (2020) has shown that the variability of the rainfall over ocean is influenced by the variability in the surface latent heat flux. A reduction of the bias over the ocean will have an impact on the accuracy of the prediction of rainfall over land. Hence there is a need for improvement in accuracy of prediction of latent heat fluxes by coupled ocean-atmosphere models. Palmer and Stevens (2019) have highlighted the need for bold new approaches to tackle the prediction of climate change on regional scales.

References

Gadgil, S., 2018: The monsoon system: Land-sea breeze or the ITCZ?, *J. Earth Syst. Sci.*, 127, 1-29, https://www.ias.ac.in/article/fulltext/jess/127/01/0001.

Jalihal, C., Srinivasan, J. and Chakraborty, A., 2019: Modulation of Indian monsoon by water vapor and cloud feedback over the past 22,000 years, *Nat. Commun.*, 10, 1-8, https://doi.org/10.1038/s41467-019-13754-6.

Jalihal, C., Srinivasan, J. and Chakraborty, A., 2020: Different precipitation response over land and ocean to orbital and greenhouse gas forcing, *Sci. Rep.,* 10, 11891, https://doi.org/10.1038/s41598-020-68346-y.

Ham, Y., Kim, J. and Luo, J., 2019: Deep learning for multi-year ENSO forecasts. *Nature*, 573, 568-572, https://doi.org/10.1038/s41586-019-1559-7.

Li, J. and Wang, B., 2016: How predictable is the anomaly pattern of the Indian summer rainfall?, *Clim. Dyn.*, 46, 2847-2861.

Neelin, J.D. and Held, I.M., 1987: Modeling tropical convergence based on the moist static energy budget, *Mon. Weather Rev.*, 115, 3-12.

Pai, D.S. and Rajeevan, M.N., 2009: Summer monsoon onset over Kerala: New definition and prediction, *J. Earth Syst. Sci.*, 118, 123-135, https://www.ias.ac.in/article/fulltext/jess/118/02/0123-0135.

Palmer, T.N. and Stevens, B., 2019: The scientific challenge of understanding and estimating climate change, *Proc. Natl. Acad. Sci. U.S.A.,* 116, 24390-2439.

Pattanaik, D.R. and Kumar, A., 2015: A hybrid model based on latest version of NCEP CFS coupled model for Indian monsoon rainfall forecast, *Atmospheric Sci. Lett.*, 16, 10-21.

Pattanaik, D.R. et al., 2020: Active-Break Transitions of Monsoons Over India as Predicted by Coupled Model Ensembles, *Pure Appl. Geophys.*, https://doi.org/10.1007/s00024-020-02503-2.

Rajendran, K. et al., 2012: Monsoon circulation interaction with Western Ghats orography under changing climate, *Theor. Appl. Climatol.*, 110, 555-571.

Srinivasan, J., 2001: A simple thermodynamic model for seasonal variation of monsoon rainfall. *Curr. Sci.*, 80, 73-77.

Wang, B. et al., 2015: Rethinking Indian monsoon rainfall prediction in the context of recent global warming. *Nat. Commun.*, 6, 7154, https://doi.org/10.1038/ncomms8154.

Wedi, N.P., et al., 2020: A baseline for global weather and climate simulations at 1 km resolution, *J. Adv. Model. Earth Syst.*, Online (Open Access), https://doi.org/10.1029/2020MS002192.

Weisheimer, A. and Palmer, T.N., 2014: On the reliability of seasonal climate forecasts. *J. R. Soc. Interface,* 11: 20131162. http://dx.doi.org/10.1098/rsif.2013.1162.

Monsoon Mission Overview

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1. Introduction

Monsoons dictate life in the Indian region including its economy. While the economy in recent years has been 'monsoon proofed' to a large extent, a weak monsoon can still impact the economy significantly. While famines are a thing of the past, droughts certainly can put pressure on the economy. It is not just the occurrence of a drought but lack of prior information regarding its occurrence that has led to economic problems for India. A good prediction of the monsoon is essential for the government to take appropriate measures well in advance so that the effects of a drought can be mitigated to a large extent. Also, the occurrence of a good rainfall, if predicted at a significant lead, can have immense benefits for all sections of the public. A good seasonal forecast can gear up the government machinery to take appropriate action. Reservoirs can be operated optimally, and water released for irrigation if accurate forecasts are available on intraseasonal (10-30 day) scale. A good intraseasonal forecast can also be useful to farmers for the agricultural operations. Accurate short-range forecasts can be of immense benefit to many users including disaster management authorities and the general public.

Major droughts of the early 21st century (2002 and 2004) were a wake-up call for serious action. After much thought and discussions, it was decided that a mission-mode project with definite deliverables was immediately required to improve monsoon forecasts at all time scales.

2. The Monsoon Mission Initiative

Monsoon Mission (MM) is a targeted activity taken up by the Ministry of Earth Sciences (MoES), Government of India, to improve monsoon weather and climate forecasts over India and increase its use in the decision-making process of weather and climate sensitive sectors such as agriculture, water, health, energy etc. Four research and operational centers of MoES (Indian Institute of Tropical Meteorology (IITM), National Centre for Medium-Range Weather Forecast (NCMRWF), Indian National Centre for Ocean Information and Services (INCOIS) and India Meteorological Department (IMD)) have actively participated in this initiative. The MM was launched in 2012 with the following objectives:

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

Prior to the launch of the MM, monsoon seasonal forecasts were based mainly on statistical models and short-range forecasts were based on coarse resolution atmospheric models. There was no system for the extended range forecasts – a huge gap. The modelling activities, including those in the research domain, were based on a variety of stand-alone models. Also, there was no High-Performance Computer (HPC) that could be used on a dedicated basis for model development and operational purposes to satisfy the requirements of forecasts at all time scales. A comprehensive review of the MM is available in Rao et al. (2019).

The MM is being executed in a phase-wise manner, each phase with an overarching and measurable scientific goal in advancing monsoon knowledge and practice; the first phase (MM-I) was implemented during 2012-2017 and the second phase (MM-II, 2017-2021) is currently in progress. In addition to the involvement of the above four organizations from MoES, participation opportunities have been extended to several other research and operational institutions worldwide by inviting proposals to work on the overall improvement of the skill of the models of interest to MoES (viz., Climate Forecast System (CFS)/Global Forecasting System (GFS) models of the National Centres for Environmental Prediction (NCEP), USA and UK Met Office models). MoES funded 30 research proposals in MM-I and 20 research proposals in MM-II. The major focus of MM-I was on setting up a dynamical modelling framework with reasonable skill for weather and climate forecasts. The focus of MM-II is on applications of these forecasts to different user sectors (e.g., agriculture, hydrology, wind/solar power, etc.) in addition to improving prediction of weather/climate extremes.

3. Implementation of Monsoon Mission

The MM is quite unique because for the first time, Government of India supported extra-mural funding for research entities from abroad. The overarching idea has been to globally tap the best of talent to improve monsoon predictions.

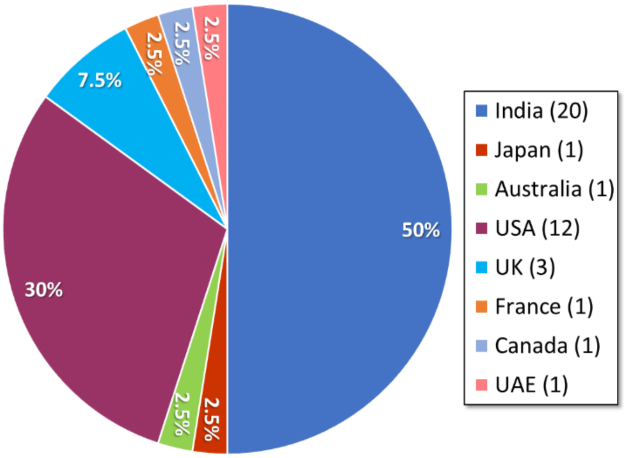

Fig.1: Distribution of country-wise approved Monsoon Mission-I projects.

The administrative structure of MM consisted of (a) Scientific Steering Committee (SSC), the apex decision-making body (b) MM Directorate and (c) Scientific Review and Monitoring Committee (SRMC).

The reach-out to global talent was through an open call for proposals which was well-publicized both in print and on the Internet. Suitable proposals relevant to the objectives of the MM, following peer-review and recommendations by the SRMC, were approved by the SSC for funding. The country-wise distribution of the projects funded in in MM-I shown in Fig. 1. The same procedure was used for MM-II.

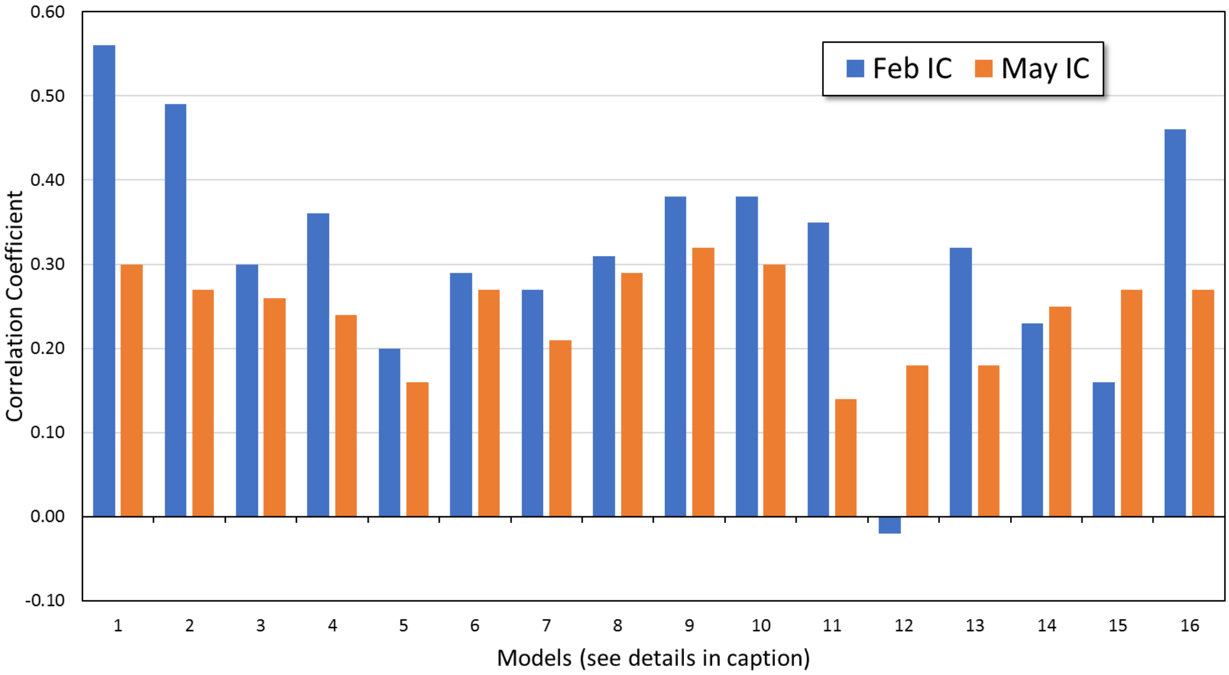

Fig. 2: Skills in forecasting Indian Summer Monsoon Rainfall (ISMR) with February and May initial conditions (correlation between observed ISMR and re-forecasted ISMR) by different models. The models corresponding to the numbers on the category axis are: (1) MMCFS; (2) CFSv2-T126; (3) CanCM3; (4) CanCM4; (5) CCSM3; (6) CCSM4; (7) GFDL-CM2p1; (8) GFDL-CM2p1a; (9) GFDL-CM2p5_Flora; (10) GFDL-CM2p5_Florb; (11) ECHAM4-Anomlay Coupled; (12) ECHAM4 DIRECTLY Coupled; (13) NASA-GMAO; (14) NASA-GMAO06; (15) ECMWF-Sys4; (16) SINTEX-F2. Hindcast period for models 1-14 is 1981-2010, while for models 15 and 16 it is 1982-2009 and 1983-2015 respectively.

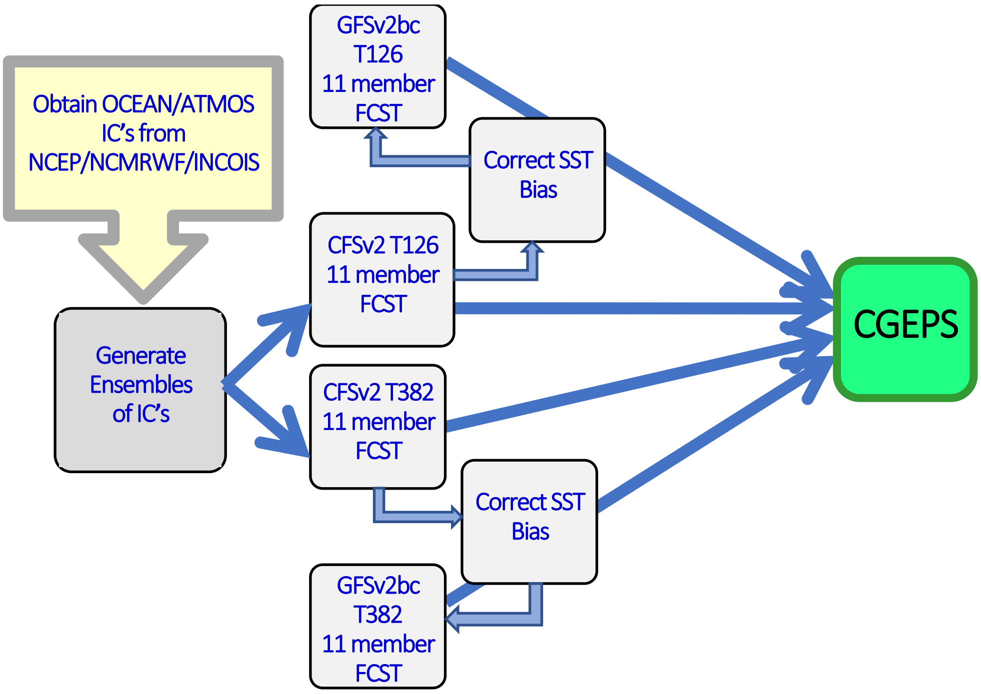

Fig. 3: Schematic representation of Coupled Grand Ensemble Prediction System (CGEPS) (After Rao et al., 2019).

4. Major Highlights of Monsoon Mission First Phase

- Best-in-class seasonal prediction model – the Monsoon Mission Climate Forecast System (MMCFS) (for monsoon prediction);
- A major gap in extended-range prediction (ERP) was plugged with the development of ERPAS models;
- Highest resolution short-range ensemble prediction model for short range forecasts;
- A weakly coupled data assimilation system using Local Ensemble Transform Kalman Filter (LETKF);
- A dedicated HPC system for model development at IITM (790 Tera Flops) and for operational purposes at NCMRWF (350 Tera Flops);
- Capability built-up in house to conduct research on various aspects of models e.g., super-parameterization, stochastic parameterization, convective parametrization, cloud microphysics parameterization, Land Surface modelling, etc.;
- NCMRWF Unified Model (NCUM) with versions developed for seasonal, extended-range, medium-range and short-range forecasts, including a regional version developed for high-resolution forecasts of air quality etc. over the North Indian region (more details in Rao et al., 2020).

Seasonal Prediction of Indian Summer Monsoon

The model developed under the MM has the highest resolution (at ~37.5km), with the best skill for forecasting the Indian Summer Monsoon (Fig. 2). This has been operationalized by the IMD since the monsoon of 2017. To sample the entire input space and to reduce errors due to uncertainties in initial conditions, an ensemble prediction system is used with 21 members. The ensemble is created by using lagged initial conditions. The forecasts are made available on IMD website (http://www.imdpune.gov.in/Clim_Pred_LRF_New/Models.html). In addition to rainfall, temperature forecasts etc. climate outlooks for the Indian Ocean Dipole Mode Index and El Niño are also updated monthly.

Extended Range Prediction (ERP)

Prior to 2012, there were no dynamical tools available in the country for ERP (beyond 10 days). This was a new effort and uses information from both coupled model (CFS) and standalone AGCM (GFS) at a variety of resolutions (Fig. 3).

The GFS is forced with bias-corrected sea surface temperatures generated from coupled forecasts. To ensure that the entire input space is sampled, ensembles of GFS/CFS are used and a multi-model ensemble used to predict the conditions at extended range. The skill is comparable to those of other centres e.g., European Centre for Medium-Range Weather Forecasts (ECMWF) (Fig. 4). This effort is not limited to monsoon forecasts and has been extended to operationalize the forecasts of heat/cold waves. ERP products are now extensively used for many applications like heat action plans, water resources management and climate-sensitive health advisories.

Short-Range Forecasts

A high-resolution forecast system based on GFS at T-1574 (~12km) was developed as part of the MM. However, an ensemble version could not be developed in the initial stages due to lack of adequate computational facilities. Upon

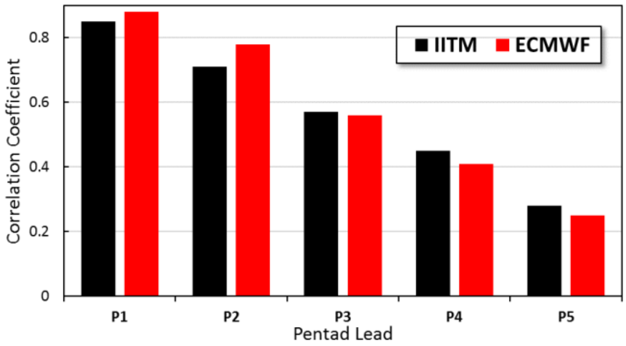

Fig. 4: Comparison of correlation skills of IITM CGEPS and ECMWF ensemble forecast (CY41R2 version) for the core Monsoon Zone of India (adapted from Rao et al., 2019).

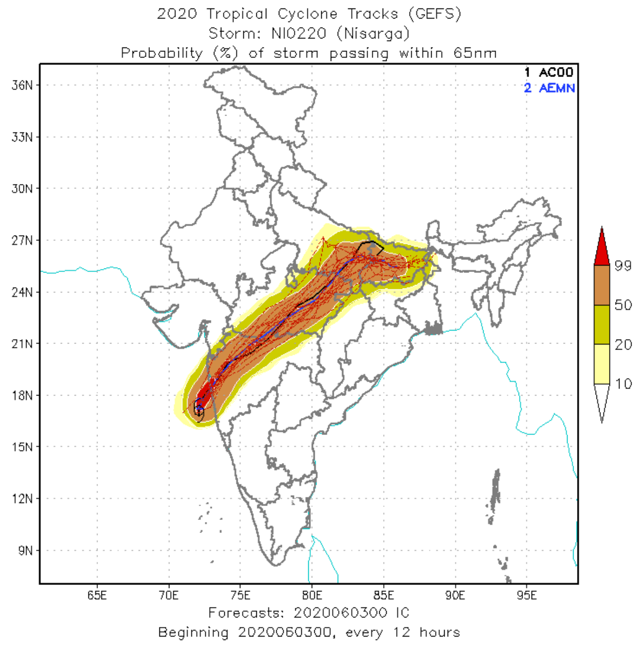

Fig. 5: GEFS Strike Probability and tracks of Tropical Cyclone *Nisarga* by individual ensemble members of evolving Arabian Sea system based on IC 03JUNE 2020 00UTC (Deshpande et al., 2020).

upgradation to 4.8 PFlops (*Pratyush* system at IITM; http://pratyush.tropmet.res.in/) towards the conclusion of MM-I, the Global Ensemble Forecast System (GEFS) was implemented in a record time of six months and operationalized by IMD for the monsoon season of 2018. The model has been a useful for predicting extreme events such as tropical cyclones (e.g., Fig. 5), heat waves and high rainfall events etc. The forecast products are now extensively used in identifying hotspots of forest fires, forecasting of solar energy and wind power etc.

Other Scientific Achievements

The interaction with academia and other research institutions within the country and abroad has yielded rich dividends. Most importantly, the scientists in various MoES organizations have undertaken independent research in various fields. A few examples are given below:

- A weakly coupled data assimilation system based on LETKF developed in collaboration with University of Maryland, USA;
- Improvements in cloud-convection parameterization including stochastic parameterization, super-parameterization and their implementation in CFS;
- Improvements in land surface processes;
- Coupling of hydrology/river routing model to CFS to represent realistic freshwater flux to the Ocean.

Identification of Gaps

The first phase was quite successful in developing an operational forecast system across all time scales. It also helped in identification of gap areas, particularly related to:

- Model numerics and dynamics;
- Application of forecasts for various societal applications;
- Better representation of monsoon teleconnections;
- Simulating and predicting extreme events across scales.

5. Monsoon Mission Second Phase

The success of MM-I enthused the Government of India to embark on the second phase of this ambitious programme. Based on the gaps identified, it was decided that in addition to further development of models at various scales, importance needed to be given to application of downstream models that could use forecasts effectively. Emphasis in this phase has been on agriculture, hydrology and non-conventional energy sectors. Additionally, focus has also been laid on improving model dynamics and numerics for CFS.

In the field of agriculture, interaction is now going on with organizations such as the Indian Council for Agricultural Research (ICAR) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) on possible uses of climate data and forecasts for various crops (peanuts, soybean and pigeon pea etc.). In non-conventional energy sector, collaboration has been initiated with institutes like Imperial College, UK for applications in wind power, solar energy etc. Experimental products are now generated for private industries in the energy sector. Collaboration also has been initiated in the area of model numerics and dynamics with the Indian Institute of Technology (IIT) Kanpur and University of Tokyo, Japan. A dynamical core based on icosahedral technique is to be developed under this collaboration. In-house developmental activities have also been initiated on new dynamical cores based on cubic octahedral spectral techniques. These will be implemented in GFS/CFS.

Another major area that needed further research is on teleconnections affecting the Indian monsoon. Most models have a stronger-than-observed linkage to ENSO while the linkage with Indian Ocean is weak or non-existent. CFS also has similar issues and MM-II has a special focus for research to address this. In addition, new areas have also been identified for developing models. These include thunderstorm forecasting, air quality forecasting using high-resolution regional models with GFS model output as initial and boundary conditions.

Thunderstorm forecasting: Thunderstorms and associated lightning cause large numbers of casualties in India. Hence in-house development of thunderstorm forecasting systems has been initiated at IITM under MM. These are based on Weather Research and Forecasting (WRF) and GEFS models. These have now been operationalized and the products are available at: (https://srf.tropmet.res.in/srf/ts_prediction_system/index.php).

Air Quality Forecasting: Air quality has been a major cause of concern especially during winter months in the National Capital Region. A high-resolution system which includes chemical data assimilation has been developed by IITM in collaboration with the National Center for Atmospheric Research (NCAR), USA. The forecast is done at a resolution of 400m, among the highest for such air quality forecasts. Chemical data assimilation includes data from satellite and ground stations (https://ews.tropmet.res.in/analysis.php).

Forecasts for Hydrological Sector: As a downstream product, Qualitative Precipitation Forecasts are being generated for major river basins of the country using forecasts from GEFS. These help in quantifying rainfall at smaller scales that could be useful for river basins.

High Temporal/spatial resolution Rainfall Datasets: Model development and validation needs good observational data at high spatial and temporal resolution. For this purpose, a project is underway to create rainfall datasets (2 km at 10-min resolution) by blending gauge, radar, satellite and NWP data to create a comprehensive high-resolution dataset.

6. Way Forward

We have seen that forecasting of weather and climate on a wide range of time and space scales has come of age in India during the last decade, thanks largely due to the concerted efforts under the MM. Today the country's forecasting capabilities are at par with the most advanced in the world. However, it is necessary that we do not rest on our laurels but continue developing improved models and products that could be useful not only for various sectors in India but also the other countries of the world, especially in the neighborhood of India. To assess the economic impact of forecasts, MoES had commissioned a study by the National Council of Applied Economic Research (NCAER), which has highlighted the dramatic impact of forecasts on two sectors, viz., agriculture and fisheries (NCAER, 2020). The major finding of this study is that the economic impact on these two sectors is about 50 times the investment made by the government on HPC and the MM. About 10 billion Indian Rupees (about US$135 million) were invested in MM and HPC, and the economic gain over a five-year period is estimated to be about 505 billion Indian Rupees (about US$6.8 billion).

It is necessary that a more synergistic approach be undertaken for use of sub-components in models across scales for optimal utilization of resources. IITM has for this purpose come out with a road map for model development (IITM, 2020) with emphasis on seamless prediction systems. This includes interoperability of models across scales and sharing of routines such as cloud convection schemes etc. Optimization of resources also requires model codes to be highly scalable and to efficiently use the latest technologies in HPC. It is proposed that emergent technologies such as graphical processing units (GPUs) be exploited for economizing on computational and energy resources. Research on these issues is at a nascent stage in India and needs to be nurtured.

The prediction models generate huge amounts of data and it is humanly almost impossible to analyze these using conventional techniques. Additionally, new techniques such as Artificial Intelligence (AI) and Machine Learning (ML) are maturing rapidly and could be put to innovative use not just for data analytics but also innovating with models and products. Latest research is concentrated on (i) embedding AI/ML inside models to replace conventional empirical computations such as cloud convection parameterization (ii) enriching and improving model forecasts offline by reducing errors and biases (iii) innovative downstream application products using these techniques.

New satellites are being launched by different countries that are dedicated for studying climate and weather. The data from these satellites need to be used to improve initial conditions for models and also for improving empirical parts of the model. Data Assimilation is a key topic for development for the future. Experience has shown that ocean-atmospheric coupling for conducting data assimilation is a promising way forward for improving initial conditions. It is proposed to carry forward research on this important topic.

Last but not the least, India needs more good quality scientists and engineers to tackle these problems. Forecasting weather and climate is an interdisciplinary field which needs meteorologists, oceanographers, computational scientists and engineers. While a single individual may not have all these diverse skills, it is necessary to have a more all-encompassing approach for training our future generations.

In short, it can be said that India has taken impressive strides and quantum jump in the field of forecasting weather and climate especially in the last decade. However much more needs to be done to improve the forecasts on all time scales and reduce uncertainties. The momentum gained in the first two phases of MM needs to be maintained for India to have high-quality forecasts keeping up with the best in the world and more importantly to meet the increasing requirements of the users in India as well as to support the regional and global communities.

References

Deshpande M. et al., 2020: Implementation of Global Ensemble Forecast System (GEFS) at 12km Resolution. IITM Techical Report TR-6/2020 https://www.tropmet.res.in/~lip/Publication/Technical-Reports/TR-6.pdf.

IITM, 2020: Roadmap for IITM model development: Towards seamless prediction of monsoon weather and climate. Technical Report No.TR-05, ISSN 0252-1075, https://www.tropmet.res.in/~lip/Publication/Technical-Reports/TR-5.pdf.

NCAER, 2020: Estimating the economic benefits of Investment in Monsoon Mission and High Performance Computing facilities, National Council of Applied Economic Research, New Delhi, India, Report No. 20200701, 76pp, https://moes.gov.in/writereaddata/files/Economic_Benefits_NCAER_Report.pdf.

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Amer. Meteor. Soc.*, 100, 2509-2532, https://doi.org/10.1175/BAMS-D-17-0330.1.

Rao, S.A. et al., 2020: Major Achievements of Monsoon Mission. *CLIVAR Exchanges*, 79 (this issue), 10-15.

Major Achievements of Monsoon Mission

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1. Introduction

The Monsoon Mission (MM) is a targeted activity taken up by the Ministry of Earth Sciences (MoES), Government of India, is coordinated by the Indian Institute of Tropical Meteorology (IITM), by making calls for proposals, by actively participating in developing models for short-, medium-, extended-, and long-range forecasts based on Climate Forecast System (CFS)/Global Forecasting System (GFS) models of the National Centres for Environmental Prediction (NCEP), USA, and by setting up the required high-performance computers both at IITM and the National Centre for Medium Range Weather Forecasting (NCMRWF). NCMRWF has carried out work on the implementation of the UK Met Office (UKMO) based seamless Unified Model (UM) for making forecasts at all time scales and has also been involved in preparing initial atmospheric conditions based on GFS modelling framework and UKMO framework. The Indian National Centre for Ocean Information and Services (INCOIS) is actively engaged in making ocean initial conditions based on the Global Ocean Data Assimilation System (GODAS) for extended- and long-range forecasts. NCMRWF implemented a NEMO (Nucleus for European Modelling of the Ocean) based global ocean Data assimilation system. IMD implemented all the developmental activities of IITM for their operational services by taking atmospheric initial conditions (ICs) from NCMRWF and oceanic ICs from INCOIS and by taking guidance of NCMRWF model forecasts based on UM modelling system. MM was executed in 2 phases (MM-I, 2012-2017 and MM-II 2017-2021) and this article briefly outlines the significant achievements of both the phases. Details of the achievements of MM-I were already reported by Rao et al. (2019).

2. Major Achievements

(i) **Human Capital**: A strong working partnership is established between MoES institutes and several research institutes worldwide (30 in MM-I and 21 in MM-II) to work on Indian monsoon related problems and to develop models adopted by MoES institutes. MM program resulted in publication of around 300 research papers, about 22 students awarded Ph.Ds (7 submitted), and 10 MoES scientists were trained abroad on various techniques of dynamical modelling. All this has been achieved with an investment of 12 million US$ in MM-I and 5 million US$ in MM-II, excluding the cost of high-performance computers.

(ii) Development of dynamical models

(a) Seasonal Prediction model: Best seasonal prediction model (MMCFS) for Indian Summer Monsoon Rainfall (ISMR) was developed with a skill which was never achieved earlier by dynamical models. The model captured almost all droughts (Ramu et al., 2016) that occurred during the hindcast period (1982-2009).

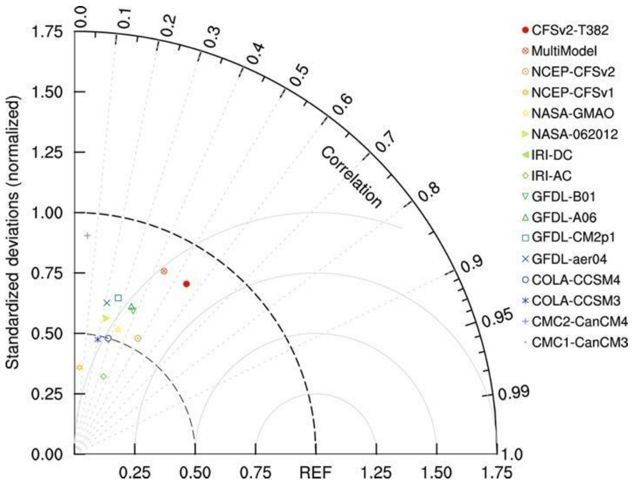

Fig. 1: Taylor diagram showing the skill and SD of ISMR (rainfall averaged over land points for the models (Source: Pillai et al., 2018).

(b) Extended Range Prediction (ERP) model: A Coupled Grand Ensemble Prediction System (CGEPS; for details, see Nanjundiah and Rao, 2020) model for predicting active-break cycles in extended range time scales was developed for the first time in India with skills comparable to ENS ECMWF (Chattopadhyay et al., 2018). Pattanaik et al. (2020) have shown that the operational

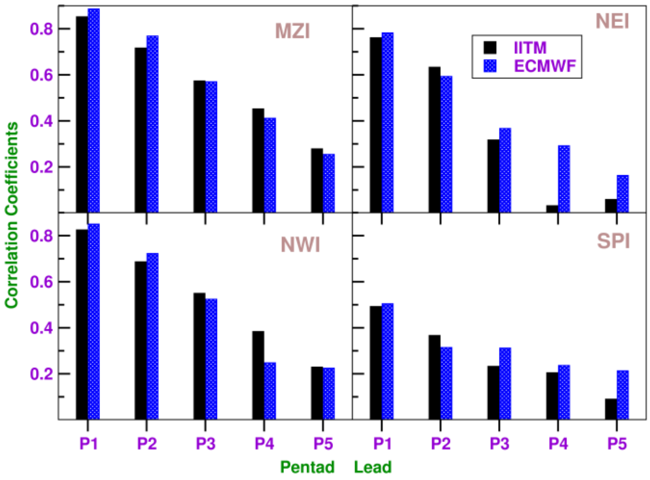

Fig.2: Comparison of correlation skills of IITM CGEPS and ECMWF ensemble forecast (CY41R2 version) for the four homogeneous regions of India (MZI: Monsoon Zone of India, NEI: North East of India, NWI: Northwest of India, SPI: Southern Peninsular India). Skill score is based on 11 members from each of ECMF ENS and IITM MME (Source: Chattopadhyay et al., 2018).

extended-range forecast has good fidelity in predicting the active-break-active transitions of the monsoon during 2017 and 2018 and the forecast of all-India and central India rainfall during the active-break-active transition phases of the monsoon are very well captured with a lead time of 2-3 weeks.

(c) Short- and Medium-range weather forecasts: A very high resolution (~12.5 km), deterministic (Mukhopadhyay et al., 2019) and probabilistic forecasting system with 21 members for short- and medium-range (up to 10 days) forecast has been set up at IITM/IMD to make operational weather forecasts. During the MM period, a gain of 2 days lead time is achieved (Fig.3); the threshold skill of 0.225 Peirce skill score is obtained with high-resolution deterministic models (T1534) at 5-day lead which coincides with 3-day lead skill score with low-resolution model (T574).

(d) Seamless modelling framework: NCMRWF implemented UM based seamless modelling framework having components as (a) UM atmosphere (b) NEMO ocean (c) CICE sea-ice model and (d) JULES land-surface model. A NEMO based global ocean data assimilation was also implemented to initialize the ocean component of the coupled model. The coupled modelling system started producing real-time extended range forecasts (multi-week) up to four weeks from the monsoon 2018 season on an experimental basis. The atmosphere and land components of the models were initialized with the respective assimilation systems. The model could capture the dry/wet spells of monsoon realistically. Fig. 4 shows examples of wet and dry spells during monsoon 2019 captured well by the coupled model.

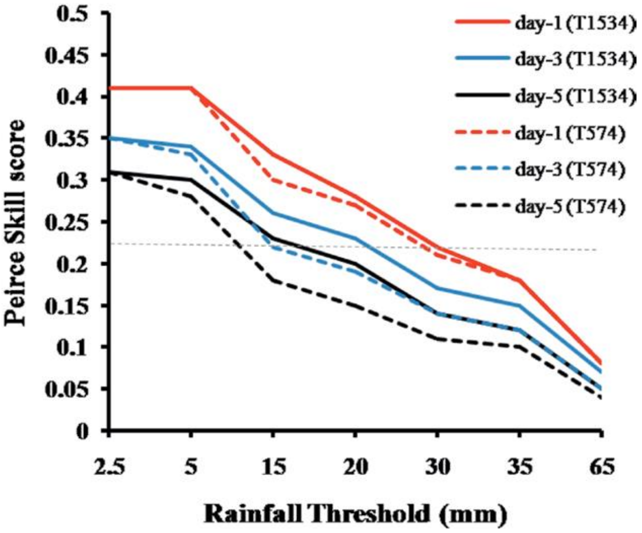

Fig.3: Forecast skill (Peirce skill score) for different rainfall threshold values for day 1, day 3, and day 5 forecast of GFS system of MM for different resolutions (T1534 and T574) (Source: Rao et al., 2019).

(iii) New insights into monsoon weather and climate predictions

(a) Bias corrected method for ensemble creation: The coupled model sea surface temperatures (SSTs) suffer from strong SST biases and Abhilash et al. (2015) have developed a novel approach of including SST bias-corrected ensembles from a standalone atmospheric model Global Forecasting System of NCEP (GFS) in CGEPS. Standalone model is forced with daily bias-corrected forecast SSTs from CFSv2. This approach resulted in better prediction skills of extended range

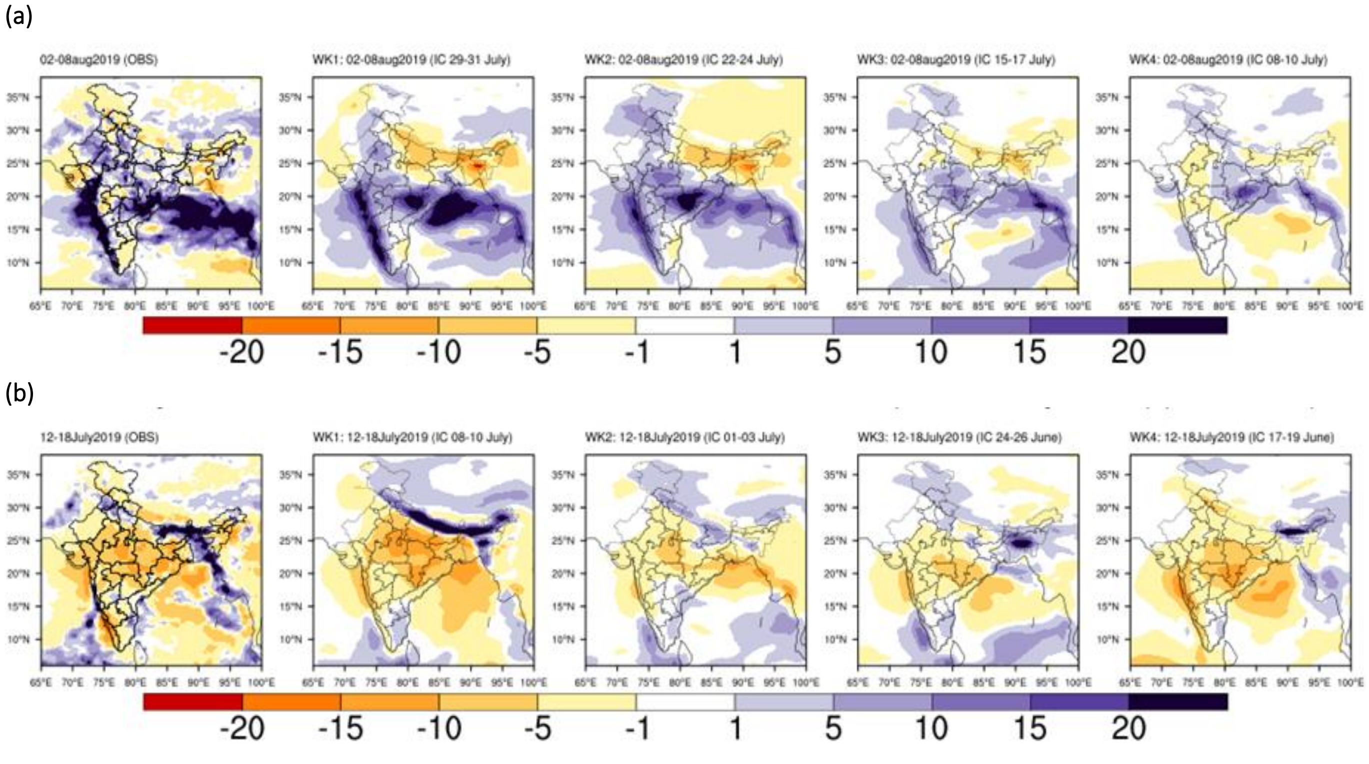

Fig. 4: Multi-week forecast validation of rainfall anomalies for ERP of (a) an active (wet) monsoon period (2-8 August 2019) and (b) a break (dry) monsoon period (12-18 July 2019).

forecasts in 4 homogenous regions of India (Abhilash et al., 2015).

(b) Better skills of long-lead over short-lead seasonal forecasts: It is for the first time that long-lead forecasts (initialized with Initial conditions of February) of seasonal forecasts of ISMR are found to be more skillful compared to short-lead forecasts (initialized with Initial conditions of May). Several reasons are proposed to highlight this unique feature by different authors: (i) Chattopadhyay et al. (2016) proposed that strong cold SST bias in the equatorial Pacific (associated with forecasts initialized with May ICs) shifts the teleconnection patterns associated with ENSO westward hence the relation between ISMR and ENSO decreases; (ii) the global teleconnection patterns associated with ISMR are well captured with long lead forecasts (Pokhrel et al., 2016); (iii) in recent decades El Niño Modoki is dominantly modulating ISMR variability, and El Niño Modokis are better captured with February initialized forecasts better compared to forecasts initialized with May ICs (Pillai et al., 2017); and (iv) model shock is vital particularly in the Arabian Sea when initialized with ICs from May (Shukla et al., 2018).

(c) Development of new data assimilation techniques: Couple data assimilation (both weakly and strongly coupled) techniques are developed and these methods also assimilate SST, sea level anomaly, etc. (more details in Da et al., 2020).

(d) Ocean analysis: Implemented Local Ensemble Transform Kalman Filter (LETKF) based data assimilation system in the global configuration of Modular Ocean Model (MOM4). The same data assimilation technique has been implemented in the Regional Ocean Modeling System (ROMS), which is part of the High-resolution Operational Ocean Forecast and analysis System (HOOFS) used for providing routine short-term ocean state forecasts by INCOIS (Francis et al., 2020).

(e) Atmospheric analysis: The atmospheric ICs for GFS systems are generated by using a grid-point statistical interpolation (GSI) based 4D-Ensemble Variational Data analysis scheme. It employs a flow dependent background error covariance by mixing a static covariance from that of 80 Ensemble members generated using Ensemble Kalman Filter (EnKF) (Prasad et al., 2016).

(f) Dynamical downscaling of extended and seasonal forecasts: ERPs were downscaled using a Weather Research and Forecasting (WRF) model with 9 Km resolution (Kaur et al., 2019). This downscaling takes advantage of good prediction skills of raw-ERP in capturing the large-scale signals and adds value by reducing spatio-temporal errors in regional detailing. This technique is an effective tool to generate useful high-resolution predictions at 10-12 days lead time. A technique using WRF model with 38 Km resolution coupled to an ocean mixed layer is developed for downscaling the seasonal forecasts from T126 (~100 km) model forecasts to 38 km resolution. It is noticed that downscaled forecasts are showing good skills comparable to those of a global high-resolution model (T382, ~38km) in addition to providing statistics of rainfall intensities at different grid points. The downscaled products were successfully utilized and found useful in farm practices at district levels (Dr Anthony Whitbread and his group, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India, *personal communication*).

(iv) Model developmental activities

(a) Super Parametrization: Super parameterized CFSv2 (SP-CFS) has been implemented for the first time at T62 (~200 km) atmospheric horizontal resolution (Goswami et al., 2015). SP-CFS improves the simulation of rainfall over India with reduced dry bias and also captures monsoon intra-seasonal oscillation (MISO) modes reasonably well.

(b) Stochastic multicloud convective parameterization: A stochastic multicloud (SMCM) cumulus parameterization is implemented in CFSv2. This implementation improves the synoptic and intra-seasonal variability in CFS (Goswami et al., 2017). For more details, see Khoudier (2020).

(c) Cloud and convective parameterization: The default CFSv2 uses a Simplified Arakawa Schubert (SAS) scheme which has many limitations such as triggering too many drizzles and having lesser percentage of deep convection. Ganai et al. (2014) have incorporated a Revised SAS (RSAS) which has significantly improved the dry bias of CFSv2 over Indian region, the diurnal variability of rainfall and monsoon mean state. The RSAS convection is subsequently being used in the seasonal, extended range and IITM Earth System Model. The RSAS is further modified to improve the CFSv2 mean state and extreme rain forecast by GFS (Ganai et al. 2019a).

(d) Cloud microphysics: It is a well-known fact that cloud microphysical processes exhibit a strong impact on rainfall and local atmospheric thermodynamics. The efforts made in MM programme showed that these processes could significantly impact the mean circulation (Hazra et al., 2017) in models. Including ICE microphysics in CFS enhances high cloud fraction (global tropics: ~59%, India: ~51%) and stratiform rain (global tropics: ~5%, India: ~15%) contribution. Following the observation-based hypothesis (Abhik et al., 2013) on the role of cloud processes to Boreal Summer Intraseasonal Oscillation (BSISO), the cloud microphysics of CFSv2 model at resolution T126 (~100km) has been improved with a more physically based cloud scheme, viz., WRF Single-Moment 6-Class microphysics scheme (WSM6). The WSM6 has been duly modified with Indian field campaign data from Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) (Abhik et al., 2017). The revised CFSv2 is found to provide an improved mean state, intra-seasonal variability, ratio of convective and stratiform proportion and hindcast skill score higher than all other modified CFSv2 and equivalent to high resolution CFSv2 at T382 (Rao et al., 2019). When the

improved WSM6 is used with an improved sub-grid scale convection, the CFSv2 is found to reproduce all the observed features and characteristics of clouds (Ganai et al., 2019b) associated with BSISO.

(e) Land Surface modelling: A multilayer (6 layers) snow scheme is introduced in CFS v2 (Saha et al., 2017). CFSv2 with the modified Noah Land-Surface Model (LSM) improves the representation of snow depth, 2m temperature and snow water equivalent in addition to reducing the dry bias over Indian landmass.

All the above model developments have now been integrated into the MMCFS model, resulting in encouraging improvements in seasonal prediction skills (Rao et al., 2019). Efforts to test the impact of these developmental activities on short and medium range predictions are underway.

(v) Focused observational Programs supported by Monsoon Mission

(a) MoES- USA's Office of Naval Research (ONR) Collaborative project in the Bay of Bengal to understand the role of ocean mixing on monsoon: This collaboration revealed for the first time to the world gives a first high-resolution view of the Bay of Bengal's ocean structure. Major outcome of this program is identification of multitude of fronts due to strong lateral salinity gradients and impact of these frontal freshwater stratification on temperature evolution at surface and subsurface (Mahadevan et al., 2016)

(b) MoES-UK's Natural Environmental Research Council (NERC) collaborative project on Drivers of Variability in the South Asian Monsoon: This project was launched in 2015 with an aim to monitor the physical processes of the monsoon through a large-scale observational campaign involving MoES, Indian Institute of Science and partners from India and UK (Vinayachandran et al., 2018; Turner et al., 2020; Pathak et al., 2019). More details about these observational programs can be found in Turner (2020) and Sengupta et al. (2020).

(vi) Application to different sectors

(a) Agriculture: Extended range forecasts are now widely used for preparing agro-met advisories (Chattopadhyay et al., 2020), and seasonal forecasts are experimentally tested and found useful in rain-fed cultivation practices in Andhra Pradesh and Karnataka (Whitbread and Dixit, ICRISAT, *personal communication*). The present ERP system is used by Central Research Institute for Dryland Agriculture (CRIDA)/IMD to generate National Agro-Met Advisory Services (NAAS) Bulletins every week. These advisories are found to be useful in strategic planning of farm operations (Chattopadhyay et al., 2018).

(b) Hydrology: The ERP data are being used in hydrological models to forecast runoff and soil moisture to estimate the agricultural and hydrological droughts severity and areal extent Shah et al. (2017).

(c) Solar/wind power: Short-range forecasts and downscaled forecasts of wind and incoming short-wave radiation are being shared with the stake holders and also government agencies such as Power System Operation Corporation Limited (POSOCO) and Western Regional Load Dispatch Centre (WRLDC), Mumbai, India. The forecasts are being evaluated every day with forecasts obtained from other leading centers such as ECMWF and the IITM generated forecasts show substantially improved skill. The skill of wind forecast of IITM has been evaluated (Gangopadhyay et al., 2019) where the forecast is found to capture the diurnal variation, probability density function (PDF) etc. over several locations of Karnataka state, India.

(d) Health: Probabilistic forecasting of the disease incidences of malaria diarrhoea in extended range time scale (2-3 weeks in advance) was developed by using forecast products of probabilities of rainfall, minimum temperature and low (moderate) maximum temperature (Sahai et al., 2020).

(e) Forest management: To monitor the region with possibility of potential forest fire, the Global Ensemble Forecast System (GEFS) forecast parameters such as moisture, 10m wind, 10m temperature etc. are being shared with Forest Survey of India (FSI), Ministry of Environment, Forest and Climate Change, Dehradun. (More details about applications can be found in Sahai et al., 2020)

3. Summary

This article provided information on major achievements of the Monsoon Mission (MM). MM Program was launched in 2012 by Ministry of Earth Sciences with a definite target to improve the weather and climate forecasts over India. MM Phase-I (MM-I) started in 2012 and concluded in 2017, while MM-II started in 2017 and is expected to conclude in 2021. Prior to the launch of MM, the relevant MoES institutes responsible for providing and improving weather and climate forecasts were using stand-alone dynamical models. MM-I provided them an opportunity for the first time to work with coupled dynamical models and also to work on very high-resolution models (30 km climate models and 12.5 km weather models). As a result of MM, India now runs the highest resolution models for both weather and climate prediction (~12.5 km ensemble prediction system for short-to-medium range forecasts; 38 km climate coupled models for extended and seasonal forecast). MM provided an opportunity to global monsoon community to come together and explore the predictive capability of monsoon and design ways to improve the same.

MM has realized its dream of setting up a reliable dynamical modelling framework with reasonable skill in predicting extremes at different scales; and Indian models' skill in predicting monsoon weather and climate is now comparable to any other leading weather and climate center in the world. Despite this quantum jump in modelling capability, some gap areas still remain that need to addressed in future phases of MM, including: (a) systematic biases in rainfall, SST, (b) predicting extremes with long leads, (c) enhancing the usefulness of the forecasts generated in different sectors to minimize the losses due to natural disasters, (d) enhancing the prediction skills of extremes at different spatial and temporal scales. It is expected that future phases of the MM will develop a unified, seamless coupled dynamical system for making forecasts from weather to decadal time scales with strongly coupled analysis for initialization.

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References:

Abhik, S. et al., 2013: Possible new mechanism for northward propagation of boreal summer intraseasonal oscillations based on TRMM and MERRA reanalysis, *Clim. Dyn.*, 40, https://doi.org/10.1007/s00382-012-1425-x, 1611-1624.

Abhik, S. et al., 2017: Revised cloud processes to improve the mean and intraseasonal variability of Indian summer monsoon in climate forecast system: Part 1, *J. Adv. Model. Earth Syst.*, 9, https://doi.org/10.1002/2016MS000819, 1-2.

Abhilash, S. et al., 2015: Improved Spread-Error Relationship and Probabilistic Prediction from the CFS-Based Grand Ensemble Prediction System. *J. Appl. Meteorol. Climatol.*, 54, 1569-1578, https://doi.org/10.1175/JAMC-D-14-0200.1.

Chattopadhyay, N. et al., 2018: Usability of extended range and seasonal weather forecast in Indian agriculture, *Mausam*, 69, January 2018, 29-44.

Chattopadhyay, R. et al., 2016: Large-scale teleconnection patterns of Indian summer monsoon as revealed by CFSv2 retrospective seasonal forecast runs. *Int. J. Climatol.*, 36: 3297-3313. https://doi.org/10.1002/joc.4556.

Chattopadhyay, R. et al., 2018: A Comparison of Extended-Range Prediction of Monsoon in the IITM-CFSv2 with ECMWF S2S Forecast System, IITM Research Report No. RR-139, ISSN 0252-1075, http://www.tropmet.res.in/~lip/Publication/RR-pdf/RR-139.pdf.

Da, C. et al., 2020: Advances in coupled data assimilation, ensemble forecasting, and assimilation of altimeter observations. *CLIVAR Exchanges,* 79 (this issue), 27-30.

Francis, P.A. et al., 2020: High-resolution Operational Ocean Forecast and reanalysis System for the Indian Ocean, *Bull. Am. Meteorol. Soc.*, 101 (8): E1340-E1356. https://doi.org/10.1175/BAMS-D-19-0083.1.

Ganai M. et al., 2014: Impact of revised simplified Arakawa-Schubert convection parameterization scheme in CFSv2 on the simulation of the Indian summer monsoon, *Clim. Dyn.* (online), 4, https://doi.org/10.1007/s00382-014-2320-4, 1-22.

Ganai M. et al., 2019a: Revised cloud and convective parameterization in CFSv2 improve the underlying processes for northward propagation of Intraseasonal oscillations as proposed by the observation-based study. *Clim. Dyn.* (online), https://doi.org/10.1007/s00382-019-04657-9, 1-13.

Ganai, M. et al., 2019b: The impact of modified fractional cloud condensate to precipitation conversion parameter in revised simplified Arakawa-Schubert convection parameterization scheme on the simulation of Indian summer Monsoon and its forecast application on an extreme rainfall event over Mumbai. *J. Geophys. Res. Atmos.*, 124. https://doi.org/10.1029/2019JD030278, 1-21.

Gangopadhyay, A. et al., 2019: Use of a weather forecast model to identify suitable sites for new wind power plants in Karnataka, *Curr. Sci.*, 117, https://doi.org/10.18520/cs/v117/i8/1347-1353, 1347-1353.

Goswami, B.B. et al., 2015: Simulation of the Indian Summer Monsoon in the Superparameterized Climate Forecast System Version 2: Preliminary Results. *J. Climate*, 28, 8988-9012, https://doi.org/10.1175/JCLI-D-14-00607.1.

Goswami, B.B. et al., 2017: Improving synoptic and intraseasonal variability in CFSv2 via stochastic representation of organized convection, *Geophys. Res. Lett.*, 44, 1104-1113, https://doi.org/10.1002/2016GL071542.

Hazra, A. et al., 2017: Effect of cloud microphysics on Indian summer monsoon precipitating clouds: A coupled climate modeling study, *J. Geophys. Res. Atmos.*, 122, 3786-3805, https://doi.org/10.1002/2016JD026106.

Khouider, B., 2020: Improving monsoon simulations through multi-scale multi-cloud parameterization. *CLIVAR Exchanges,* 79 (this issue), 34-37.

Mahadevan, A. et al., 2016: Introduction to the special issue on the Bay of Bengal: From monsoons to mixing. *Oceanography* 29(2):14-17, http://dx.doi.org/10.5670/oceanog.2016.34.

Mukhopadhyay, P. et al., 2019: Performance of a very high-resolution global forecast system model (GFS T1534) at 12.5 km over the Indian region during the 2016-2017 monsoon seasons, *J. Earth Syst. Sci.*, 128, https://doi.org/10.1007/s12040-019-1186-6, 1-18.

Nanjundiah, R.S. and Rao, S.A., 2020: Monsoon Mission Overview. *CLIVAR Exchanges,* 79 (this issue), 5-9.

Pathak, H.S. 2019: "Assessment of regional aerosol radiative effects under the SWAAMI campaign - Part 1: Quality-enhanced estimation of columnar aerosol extinction and absorption over the Indian subcontinent, *Atmos. Chem. Phys.*, 19, 11865-11886, https://doi.org/10.5194/acp-19-11865-2019.

Pattanaik, D.R. et al., 2020: Active-Break Transitions of Monsoons Over India as Predicted by Coupled Model Ensembles. *Pure Appl. Geophys*. https://doi.org/10.1007/s00024-020-02503-2.

Pillai, P.A. et al., 2018: Seasonal prediction skill of Indian summer monsoon rainfall in NMME models and monsoon mission CFSv2. *Int. J. Climatol.*, 38: e847-e861, https://doi.org/10.1002/joc.5413.

Pillai, P.A. et al., 2017: How distinct are the two flavors of El Niño in retrospective forecasts of Climate Forecast System version 2 (CFSv2)? *Clim. Dyn.,* 48**,** 3829-3854, https://doi.org/10.1007/s00382-016-3305-2.

Pokhrel, S. et al., 2016: Seasonal prediction of Indian summer monsoon rainfall in NCEP CFSv2: forecast and predictability error. *Clim. Dyn.,* 46**,** 2305-2326, https://doi.org/10.1007/s00382-015-2703-1.

Prasad, V.S., Johny, C.J. and Sodhi, J.S., 2016: Impact of 3D Var GSI-ENKF hybrid data assimilation system. *J. Earth Syst. Sci.*,125, 1509-1521, https://doi.org/10.1007/s12040-016-0761-3.

Ramu, D.A. et al., 2016: Indian summer monsoon rainfall simulation and prediction skill in the CFSv2 coupled model: Impact of atmospheric horizontal resolution, *J. Geophys. Res. Atmos.*, 121, 2205- 2221, https://doi.org/10.1002/2015JD024629.

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Am. Meteorol. Soc.*, 100, 2509-2532, https://doi.org/10.1175/BAMS-D-17-0330.1.

Saha, S.K. et al., 2017: Effects of multilayer snow scheme on the simulation of snow: Offline Noah and coupled with NCEP CFSv2, *J. Adv. Model. Earth Syst.*, 9, 271-290, https://doi.org/10.1002/2016MS000845.

Sahai, A.K. et al., 2020: Development of a probabilistic early health warning system based on meteorological parameters. *Sci. Rep.,* 10**,** 14741, https://doi.org/10.1038/s41598-020-71668-6.

Sahai, A.K. et al., 2020: Monsoon Mission Societal Applications: Agriculture, Water, Health and Energy. *CLIVAR Exchanges,* 79 (this issue), 22-26.

Sengupta, D. et al., 2020: The Monsoon Mission Field Campaign in the Bay of Bengal. *CLIVAR Exchanges,* 79 (this issue), 42-45.

Shukla, R.P. et al., 2018: Predictability and prediction of Indian summer monsoon by CFSv2: implication of the initial shock effect. *Clim. Dyn.,* 50, 159-178, https://doi.org/10.1007/s00382-017-3594-0.

Turner, A.G., 2020: Indo-UK Joint Monsoon Campaign: Projects under Monsoon Mission. *CLIVAR Exchanges,* 79 (this issue), 38-41.

Turner, A.G. et al., 2020: Interaction of convective organization with monsoon precipitation, atmosphere, surface and sea: The 2016 INCOMPASS field campaign in India. *Quart. J. Roy. Meteorol. Soc*., 146, 2828- 2852, https://doi.org/10.1002/qj.3633.

Vinayachandran, P.N. et al., 2018: BoBBLE: Ocean-Atmosphere Interaction and Its Impact on the South Asian Monsoon. *Bull. Am. Meteorol. Soc.*, **99**, 1569-1587, https://doi.org/10.1175/BAMS-D-16-0230.1.

Wang, X. and Lei, T., 2014: GSI-Based Four-Dimensional Ensemble-Variational (4DEnsVar) Data Assimilation: Formulation and Single-Resolution Experiments with Real Data for NCEP Global Forecast System. *Mon. Wea. Rev.*, 142, 3303-3325, https://doi.org/10.1175/MWR-D-13-00303.1.

Contribution of Monsoon Mission to Operational Advances: Short to Medium Range, Extended Range and Seasonal Forecasts

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1. Introduction

India experiences various types of natural hazards including cyclones, depressions, heavy rainfall, thunderstorm/Squall/ Hailstorm, floods, droughts, earthquakes, landslides, heat and cold waves, and tornadoes etc. Most of these hazards (about 80%) are hydro-meteorological in nature. The risk management of these hazards depends on several factors including (i) hazard and vulnerability analysis, (ii) preparedness and planning, (iii) early warning, (v) prevention and mitigation. The forecast and early warning is a major component for management of weather-related hazards. In 2006, the Ministry of Earth Sciences (MoES), Government of India came into existence to address the above objective by integrating all the components of earth system science. The projects like modernization of weather forecasting and early warning services of the India Meteorological Department (IMD) were taken up along with the ambitious Monsoon Mission (MM) Programme, considering the fact that monsoon is the main factor for socio-economic activity and also the major cause for many natural hazards in the Indian region. Under the MM Phase I, it was aimed to improve weather and climate forecasting over the Indian region, from short to medium range, extended range and seasonal forecasting. During MM Phase II, it is aimed at development of application tools based on global and regional models for improvement and extension of various sectoral applications.

As a result, there has been significant improvement in terms of forecast accuracy, lead periods and service delivery resulting in decrease in loss of lives due to hydrometeorological hazards, and also decision making related to the economy of the country. Here, a review is presented on the contribution of MM to operational advances in short to medium range, extended range and seasonal forecasts over the Indian region.

2. Short to Medium Range Forecasting

Under the MM Programme, there are three types of numerical weather prediction (NWP) models in MoES, viz., individual deterministic models, Multi-Model Ensemble (MME) and single model Ensemble Prediction System (EPS) for short to medium range forecasts as mentioned below (RSMC New Delhi, 2020):

- Global forecasting system (GFS) model with horizontal resolution of 12 km and forecast up to 10 days;
- Unified Model (UM) with horizontal resolution of 12 km and forecast up to 10 days;
- Global Ensemble Forecasting System (GEFS) model with horizontal resolution of 12 km and forecast up to 10 days;
- UM ensemble prediction system (UMEPS) with horizontal resolution of 12 km and forecast up to 10 days;
- Weather Research Forecast (WRF) Mesoscale model with horizontal resolution of 3 km and forecast up to 3 days;
- Unified Mesoscale regional model (horizontal resolution of 4 km and forecast up to 3 days; and
- Hurricane WRF (HWRF) for cyclone prediction with horizontal resolution of 2 km and forecast up to 5 days.

The National Centre for Environmental Prediction (NCEP), USA, based Global Forecast System (GFS) at horizontal resolution of T1534 (~12.5 km) was made operational since October 2016 (Mukhopadhyay et al., 2019). The National Centre for Medium Range Weather Forecasting (NCMRWF) Unified Model (NCUM) is based on the UM system developed under the "UM Partnership" (https://www.metoffice.gov.uk/research/approach/collaboration/unified-model/partnership). The uniqueness of the NCUM is its seamless modelling approach with the same dynamical core and parameterization schemes to provide a broad range of spatial and temporal scales of forecast from few meters to global in space and from hours-to-season in time. Various conventional and satellite observations are used in MoES data assimilation system at NCMRWF. Impact of assimilated observations on the model forecast is continually monitored using Forecast Sensitivity to Observation Impact (FSOI) system. Fig. 1 gives an example of the impact of each type of observation on the 24 hr forecast of global NCUM during June-July 2020. High resolution (4 km) NCUM regional model and WRF (3 km) regional model initial conditions are prepared with assimilation of Indian Doppler Weather Radars (especially radial winds) in addition to other satellite and conventional observations. The amount of data being assimilated has increased to 60 GB for each cycle. All these have been possible due to establishment of high-performance computing system (HPCS) in MoES with the capacity of about 10 Peta Flops.

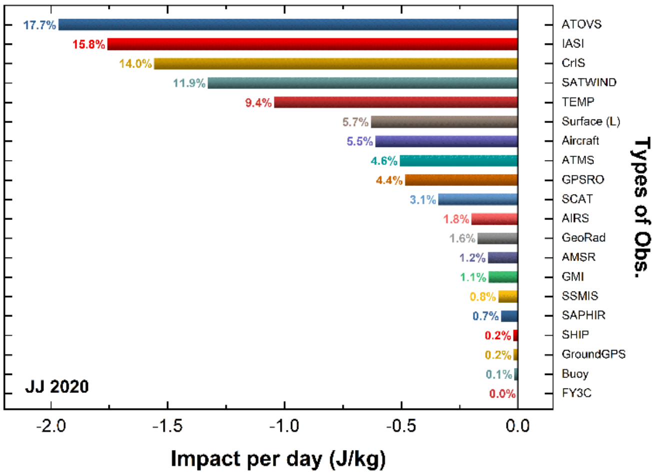
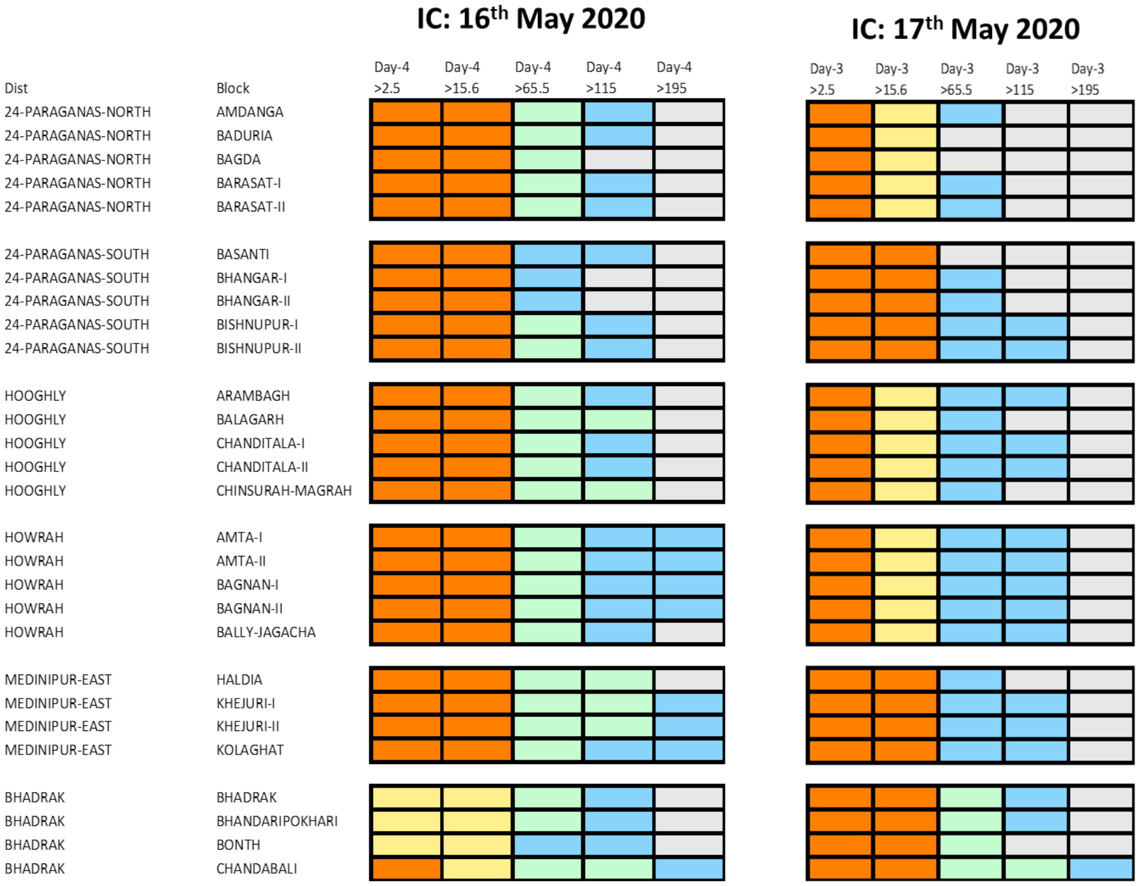


Fig.1: Relative observation impact on 24hr global NCUM forecast, obtained using operational adjoint-based FSOI approach. Large negative "impact" values indicate more beneficial impact. Statistics cover the period from 1 June to 31 July 2020.

To address the inherent uncertainties of NWP models in predicting the chaotic atmospheric flows, the EPS was started at NCMRWF at a moderate resolution of T190 in the year 2012 (Ashrit et al., 2012). It was upgraded to a globally highest resolution EPS based on GFS (at 12.5km) with 21 ensemble members since 1 June 2018 (Deshpande et al. 2020) under the MM project to improve the 10 days forecast over the country. Similarly, the 23-member NCMRWF Global Ensemble Prediction System (NEPS-G) has been made operational with resolution of ~12 km from June 2018. The NCMRWF Regional Ensemble Prediction System (NEPS-R) has also been introduced with a horizontal resolution of ~4 km and 13 ensemble members.

The establishment of the EPS marked a paradigm shift in the medium range ensemble-based forecasting in India. In the ensemble prediction system (GEFS and UMEPS) of MoES, various probabilistic forecast products are generated for severe weather events, like probabilities of occurrence of different thresholds of rainfall (heavy rain and deficient rain), temperature (heat wave and cold wave) and wind (squall and gale winds) at different locations/regions. Probabilistic quantitative precipitation forecast (PQPF) is generated for all Indian river basins with 3 to 5 days lead period. Fig. 2 shows the block level forecast probability during super cyclone *Amphan* that made landfall over Sundarbans of West Bengal, India. To provide city-specific forecast guidance, EPS-grams are prepared based on GEFS and UMEPS for every three hours up to 10 days forecast for various parameters including precipitation, wind, relative humidity and temperature at any location. Fig. 3a shows the tracks and strike probability forecasts for five days from NEPS-G and NEPS-R for the super cyclone *Amphan* in May 2020. The track forecast errors are found to be significantly less for the mean ensemble track forecast than for the deterministic forecast (Fig. 3b).

The short to medium range forecast modelling improvement under MM Programme led to (i) extension of a lead period of warning from 1 day in 2008 to 3 days in 2014, and further to 5 days in 2018; (ii) extension of cyclone track and intensity forecast from 24 hrs in 2008 to 72 hrs in 2009, and further to



Dist	Block	IC: 16th May 2020					IC: 17th May 2020				
		Day-4 >2.5	Day-4 >15.6	Day-4 >65.5	Day-4 >115	Day-4 >195	Day-3 >2.5	Day-3 >15.6	Day-3 >65.5	Day-3 >115	Day-3 >195
24-PARAGANAS-NORTH	AMDANGA	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	⬜	⬜
24-PARAGANAS-NORTH	BADURIA	🟧	🟧	🟩	🟦	⬜	🟧	🟨	⬜	⬜	⬜
24-PARAGANAS-NORTH	BAGDA	🟧	🟧	🟩	⬜	⬜	🟧	🟨	⬜	⬜	⬜
24-PARAGANAS-NORTH	BARASAT-I	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	⬜	⬜
24-PARAGANAS-NORTH	BARASAT-II	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	⬜	⬜
24-PARAGANAS-SOUTH	BASANTI	🟧	🟧	🟦	🟦	⬜	🟧	🟧	⬜	⬜	⬜
24-PARAGANAS-SOUTH	BHANGAR-I	🟧	🟧	🟦	⬜	⬜	🟧	🟧	🟦	⬜	⬜
24-PARAGANAS-SOUTH	BHANGAR-II	🟧	🟧	🟦	⬜	⬜	🟧	🟧	🟦	⬜	⬜
24-PARAGANAS-SOUTH	BISHNUPUR-I	🟧	🟧	🟩	🟦	⬜	🟧	🟧	🟦	🟦	⬜
24-PARAGANAS-SOUTH	BISHNUPUR-II	🟧	🟧	🟩	🟦	⬜	🟧	🟧	🟦	🟦	⬜
HOOGHLY	ARAMBAGH	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	🟦	⬜
HOOGHLY	BALAGARH	🟧	🟧	🟩	🟩	⬜	🟧	🟨	🟦	⬜	⬜
HOOGHLY	CHANDITALA-I	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	🟦	⬜
HOOGHLY	CHANDITALA-II	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	🟦	⬜
HOOGHLY	CHINSURAH-MAGRAH	🟧	🟧	🟩	🟩	⬜	🟧	🟨	🟦	⬜	⬜
HOWRAH	AMTA-I	🟧	🟧	🟩	🟦	🟦	🟧	🟨	🟦	🟦	⬜
HOWRAH	AMTA-II	🟧	🟧	🟩	🟦	🟦	🟧	🟨	🟦	🟦	⬜
HOWRAH	BAGNAN-I	🟧	🟧	🟩	🟦	🟦	🟧	🟨	🟦	🟦	⬜
HOWRAH	BAGNAN-II	🟧	🟧	🟩	🟦	🟦	🟧	🟨	🟦	🟦	⬜
HOWRAH	BALLY-JAGACHA	🟧	🟧	🟩	🟦	⬜	🟧	🟨	🟦	🟦	⬜
MEDINIPUR-EAST	HALDIA	🟧	🟧	🟩	🟩	⬜	🟧	🟧	🟦	⬜	⬜
MEDINIPUR-EAST	KHEJURI-I	🟧	🟧	🟩	🟩	🟦	🟧	🟧	🟦	🟦	⬜
MEDINIPUR-EAST	KHEJURI-II	🟧	🟧	🟩	🟩	🟦	🟧	🟧	🟦	🟦	⬜
MEDINIPUR-EAST	KOLAGHAT	🟧	🟧	🟩	🟦	🟦	🟧	🟧	🟦	🟦	⬜
BHADRAK	BHADRAK	🟨	🟨	🟩	🟦	⬜	🟧	🟧	🟩	🟦	⬜
BHADRAK	BHANDARIPOKHARI	🟨	🟨	🟩	🟦	⬜	🟧	🟧	🟩	🟦	⬜
BHADRAK	BONTH	🟨	🟨	🟦	🟦	⬜	🟧	🟧	🟩	⬜	⬜
BHADRAK	CHANDABALI	🟧	🟨	🟩	🟩	🟦	🟧	🟧	🟩	🟩	🟦

Fig. 2: Rainfall forecast probabilities for different thresholds over various blocks of the coastal districts (Dist) of West Bengal state of India valid for 20 May 2020 based on GEFS, with two initial conditions (ICs)/lead times (Day-4 and Day-3), during landfall of Super Cyclone *Amphan.* The numbers on top of each column of coloured boxes indicate rainfall thresholds in mm/day. The colours of the boxes stand for the corresponding forecast probabilities (orange: >75%; yellow: 50-75%; light green: 25-50%; blue: 5-25% and light grey: <5%).

120 hrs in 2013; (iii) introduction of extended range forecast (for the next two weeks) in 2016 and for cyclogenesis in 2018; (iv) district-wise impact based forecast and warning in 2018; and (v) location specific nowcast extended to 892 cities/towns in 2020 and district level nowcast for all districts since 2018. As an outcome of the MM Programme, many application-specific products were generated to improve and extend sectoral applications like disaster management, agriculture, hydrology, aviation, marine and surface transport, health and power sectors. IMD and MoES, in collaboration with the Indian Council for Agricultural Research (ICAR), State Agricultural Universities and other institutes, are rendering the weather forecast based Agrometeorological Advisory Services (AAS) to the farmers at district and block levels through a network of Agro-Met Field Units (AMFUs). An urban flood early warning system has also been developed for Chennai and Mumbai cities recently.

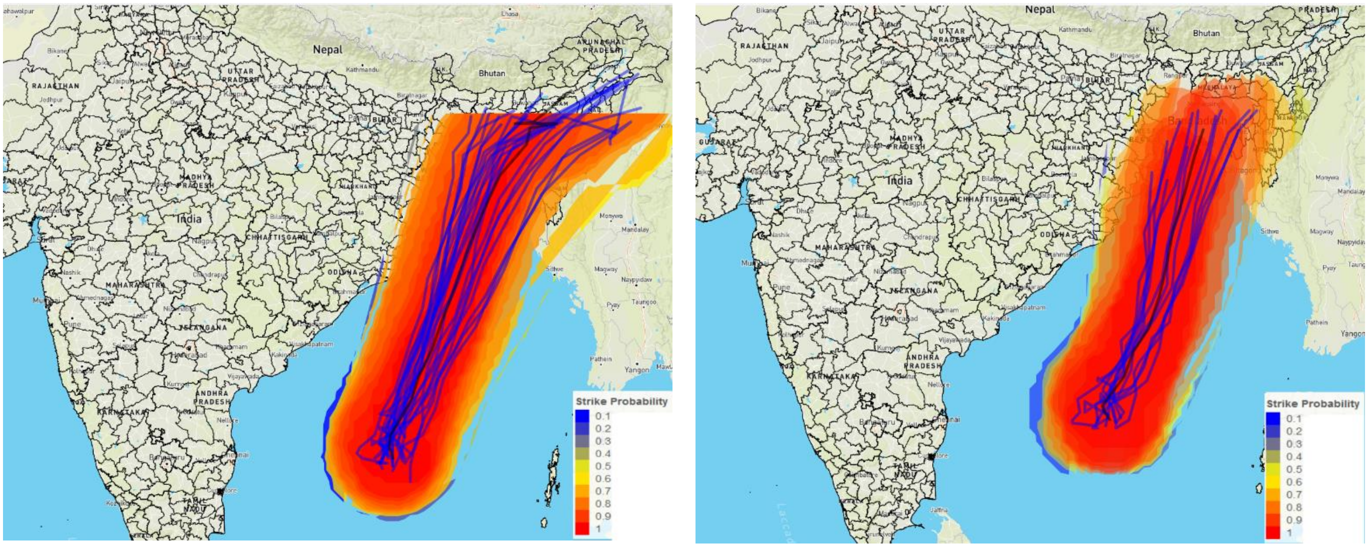


Fig. 3a: The strike probability forecasts of NEPS-G (left panel) and NEPS-R (right panel) based on 00 UTC, 18 February 2020 Super Cyclone *Amphan.*

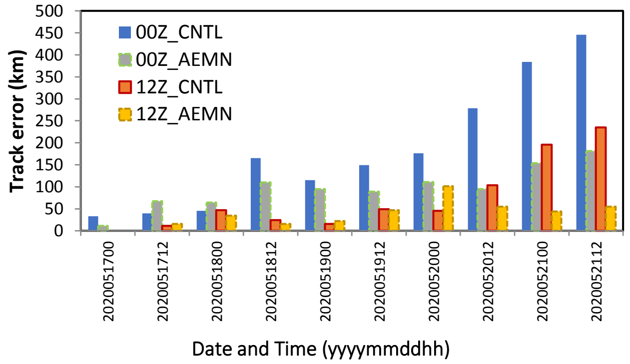


Fig. 3b: GEFS model mean ensemble track forecast error (AEMN) and deterministic GFS model track forecast error (CNTL) of super cyclone *Amphan* based on 0000 and 1200 UTC of 17 May 2020 initial conditions.

During the past 10 years, there has been significant improvement in forecast accuracy of various severe weather events including tropical cyclones, heavy rainfall, fog, heat wave, cold wave, thunderstorm (Mohapatra and Sharma, 2019; Mohapatra et al., 2020; Sen Roy et al., 2019). Between 2010 and 2019, the probability of detection in case of heavy rainfall has increased from 41% to 74% for 24-hr lead period and from 35% to 60% for 48-hr lead period. Between 2015-16 and 2017-18, the probability of detection in case of fog forecast has improved from 64% to 84% for 24-hr lead period, from 28% to 61% for 48-hr lead period. Between 2014 and 2019, the probability of detection in case of heat wave has improved from 67% to 92% for 24-hr lead period and 50% to 85% for 48-hr lead period. Between 2013 and 2019, the probability of detection of thunderstorms three hours in advance has increased from 65% to 89%. The track forecast error of tropical cyclones during 2015-19 has been 81, 126, 171 km against 107, 165, 230 km during 2010-14 for 24, 48 and 72 hrs lead periods respectively. The forecast accuracy in case of heavy rainfall and tropical cyclone over the Indian region is shown in Fig. 4(i) and (ii).

3. Extended range forecasting

Extended range forecast combined with a high-resolution short-range forecast are very useful in predicting severe weather including tropical cyclones, extreme rainfall, wet spells and dry spells, heat and cold spells etc. and thereby reducing the risk of potential disasters and loss of life (Joseph et al., 2014; Ganesh et al., 2019). It also helps in planning various activities, e.g., crop sowing, application of pesticide, and planning of irrigation (Chattopadhyay et al., 2018), dam water management (Sahai et al., 2019), health emergency warning associated with the heat waves (Mandal et al., 2019) and cold waves, vector-borne diseases (Sahai et al., 2020) and several other applications.

The current generation extended range forecast operational models are derived from NCEP (USA) as part of an international collaboration under the MM Programme (Rao et al., 2019). The current operational forecast modelling strategy is based on using 4 different versions of the same model (i.e., similar dynamical core), but in different resolutions and representation of the coupled processes (Sahai et al., 2015). These model runs are based on CFSv2 coupled model and the GFS model run at two horizontal resolutions, T126 and T382, and 64 vertical levels. Each sub-model is run as an ensemble of four perturbed initial conditions. These 16-member ensemble runs, termed as Multi-Model-Ensemble (MME), are currently generated once every week (on every Wednesday) and forecast is given for the next four weeks. The novelties of this method are (a) generating initial condition through a perturbation of the tendency term, and (b) correcting the sea surface

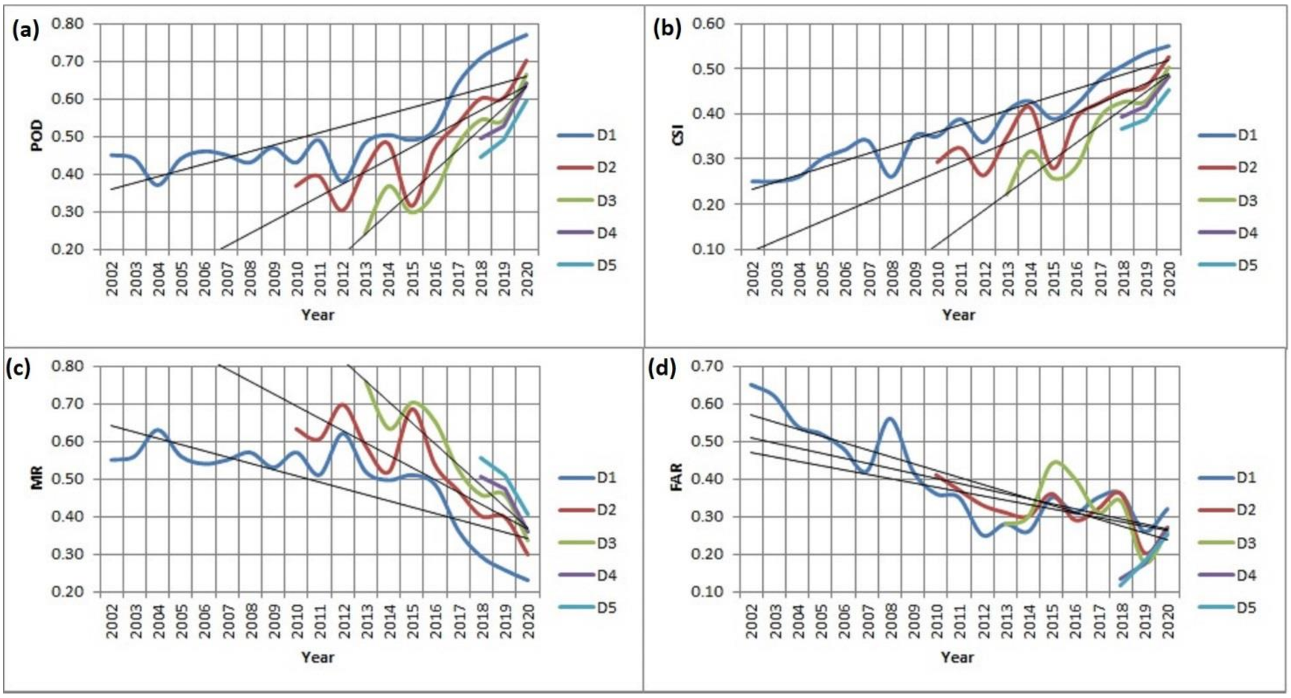


Fig. 4(i): Monsoon season (June to September) heavy rainfall skill scores namely (a) Probability of Detection (PoD), (b) Critical Success Index CSI), (c) Missing Rate (MR) and (d) False Alarm Rate (FAR) for Day 1 (D1) (2002-20), Day 2 (D2) (2010-20), Day 3 (D3) (2013-20), Day 4 (D4) (2018-20) and Day 5 (D5) (2018-20).

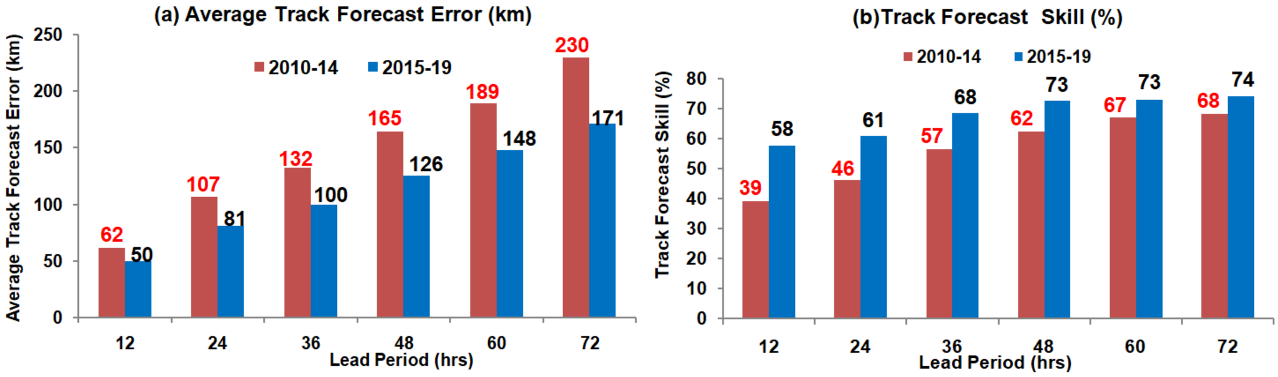


Fig. 4(ii): Average operational tropical cyclone track forecast (a) errors (km) and (b) skill (%) of IMD as compared to climatology and persistence (CLIPER) forecast during 2015-19 vis-à-vis 2010-14.

temperature bias from the coupled model run, which is used as a boundary condition to the GFS runs.

The verification of extended range forecast based on the past hindcast runs for different homogeneous regions of India as per standard IMD classification (MZI-monsoon zone of India, NEI-North East India, NWI-North West India, SPI southern peninsular India and CEI- central India) shows that up to 2-3 weeks, the MZI region has good skill in predicting the rainfall, which could be considered as statistically significant (Fig. 5). The MME has usable prediction skills up to around 18-20 days lead period. The anomaly correlation coefficient (ACC) of rainfall for the hindcast period for all pentads during JJAS shows the MME has remarkable skill over almost all parts of the country, except over Tamil Nadu in week 1 (W1) lead. Although the skill reduces with increased lead, most parts of the country have considerable skill till W3 lead. The extended range forecast is also used to track the monsoon intra-seasonal oscillations (MISO) using MISO1 and MISO2 indices (Sahai et al., 2013). The ERP system is known to have reasonable skill in predicting maximum and minimum temperatures during summer and winter seasons (Joseph et al., 2019). The system is capable of predicting the probability of occurrence of extreme temperatures (Mandal et al., 2019) and thus the onset, duration and cessation of heat and cold wave spells, albeit with some spatio-temporal errors.

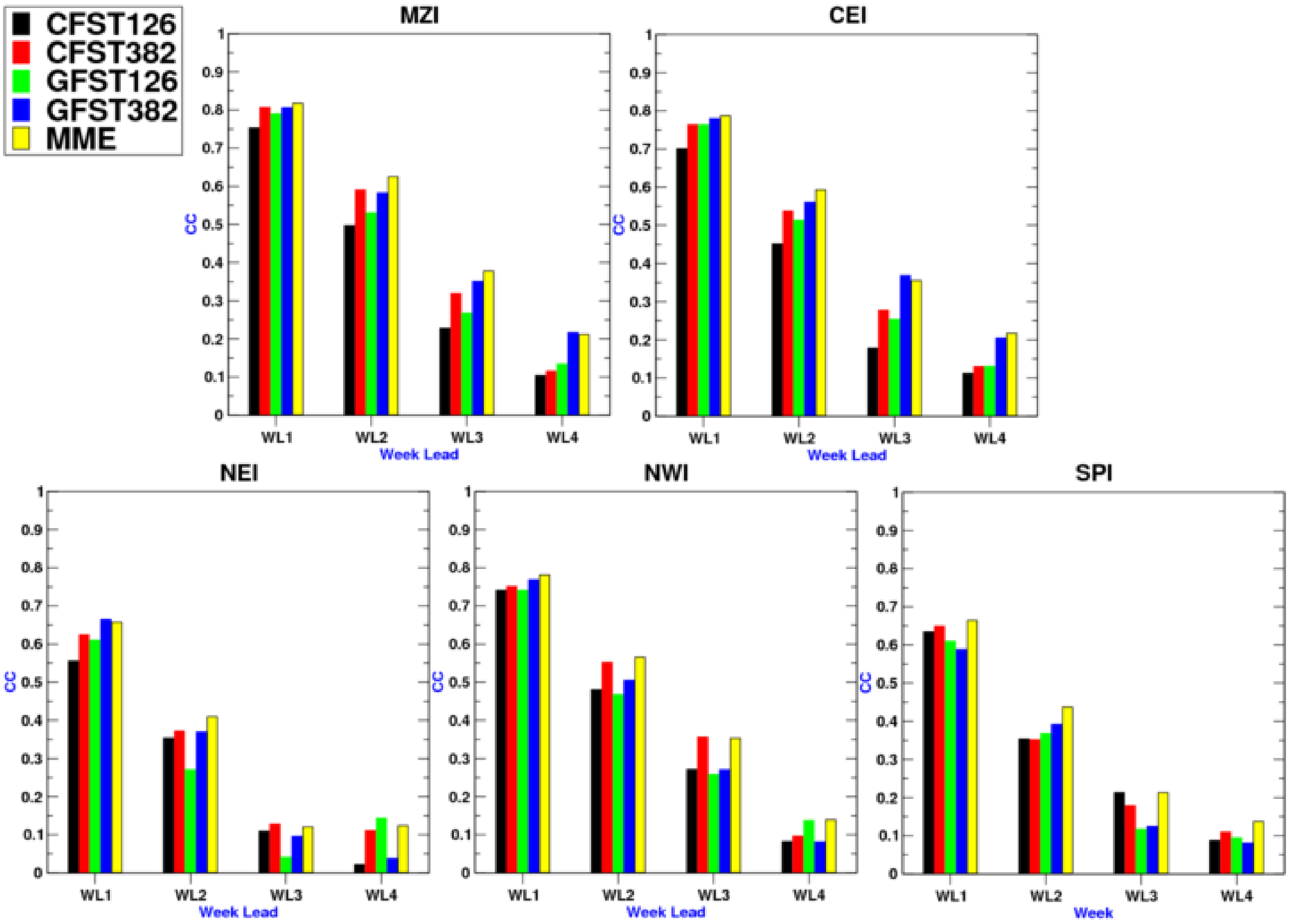


Fig. 5: The deterministic skill (CC) of weekly lead prediction by MME and individual models for area-averaged rainfall for the hindcast period (2003-2019) over the homogeneous zones of India.

4. Seasonal forecasting

The total monsoon rainfall during the monsoon season (June-September) has a statistically significant relationship with the crop yield over the country. A weak monsoon can cause a low crop yield (Parthasarathy et al., 1988) and severe droughts even influence the GDP by 2-5% (Gadgil and Gadgil, 2006). Hence, it is most important to predict the extremes in the monsoon rainfall. Preparation of experimental dynamical model seasonal forecasting of the southwest monsoon rainfall was first started in 2005 based on the Seasonal Forecast Model (SFM) of the Experimental Climate Prediction Center (ECPC) for this purpose. But the skill of these experimental forecasts based on SFM was very limited. However, the dynamical coupled forecasting system (CFS) developed during the first phase of MM Programme (MMCFS) showed useful skill in the seasonal forecasting of monsoon rainfall in 2012. The original version of the MMCFS is CFSv2 model of NCEP with a horizontal resolution of T126 (~100 km). The Indian Institute of Tropical Meteorology (IITM) made further improvements over the original version (Ramu et al., 2017) and the latest high-resolution research version of the MMCFS with horizontal resolution of approximately 38km (T382) is being used for operational monthly and seasonal forecasting along with existing Ensemble statistical forecasting system (Rajeevan et al., 2007).

Regional Climate Centre (RCC) Pune, a WMO RCC hosted by IMD, uses MMCFS to generate various monthly and seasonal forecast products for South Asia for a forecast period of up to 8 months, updated monthly. The forecast products include:

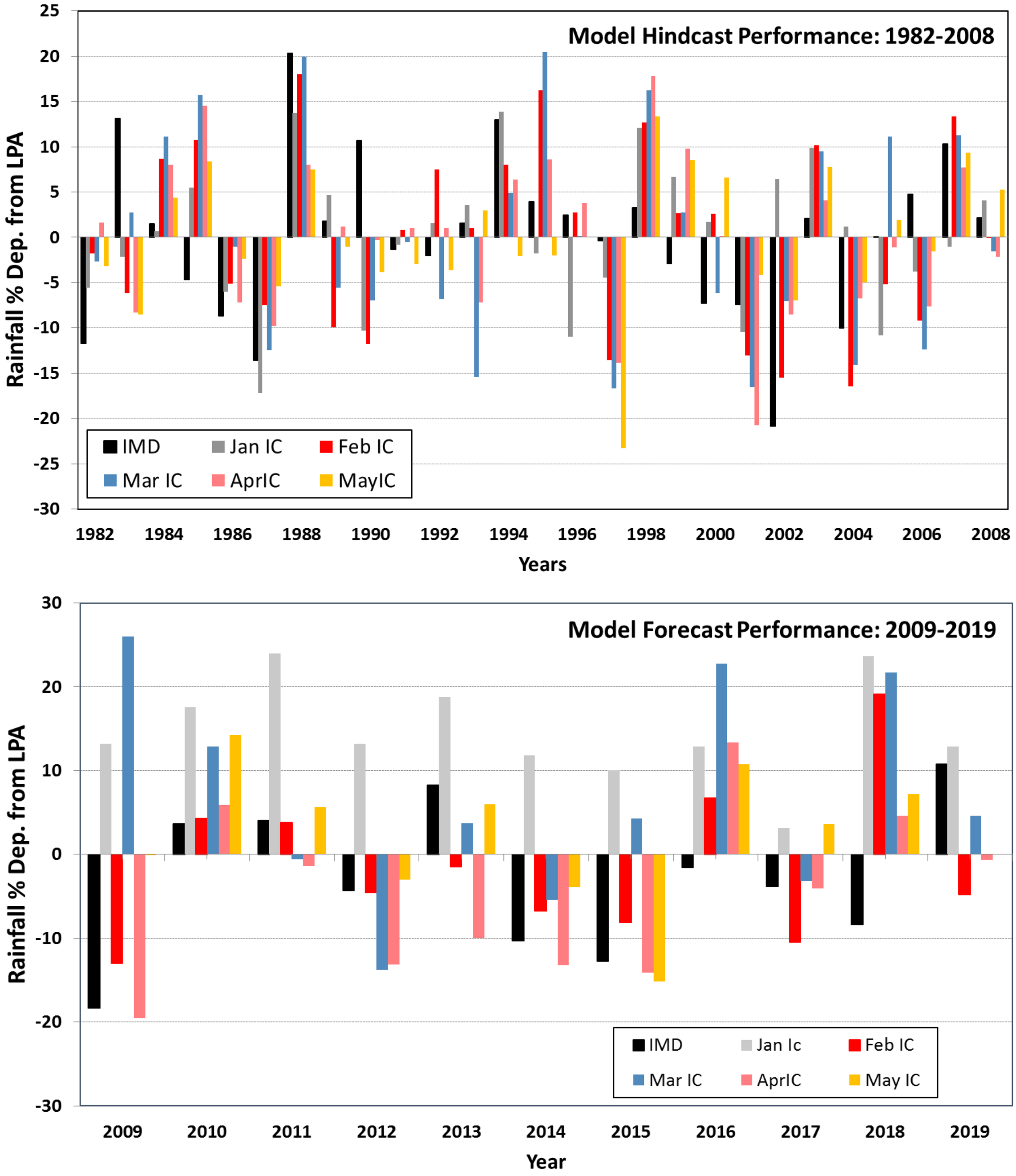


Fig. 6: Performance of the MMCFS hindcast (top) and forecasts (bottom) for the southwest monsoon season (June-September) rainfall over the country as a whole based on various initial conditions. The model forecasts were bias corrected using the z-score transformation (correction for both mean and variance) method

(i) monthly and seasonal (3-month average) rainfall and surface air temperature forecast anomaly maps; (ii) country averaged monthly rainfall and surface air temperature anomaly variation for the all the 9 South Asian countries (iii) monthly and seasonal forecast maps of global SST anomalies and forecast of El Niño/Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) indices.

The model hindcast results for the southwest monsoon season (June-September) rainfall over the country as a whole, computed based on initial conditions (ICs) pertaining to different months (January, February, March, April and May) for the period 1982-2008 showed the skills in respect to four broad homogeneous regions of India (Northeast India, Northwest India, Central India and South Peninsula). The model hindcasts and forecasts were bias-corrected using the z-score transformation (correction for both mean and variance) method (Hawkins et al., 2013). The hindcast correlation coefficient for All-India Rainfall is the highest for February IC, followed by March IC (Fig. 6). During 7 (6) years of the period 2009-2019, the Feb (March) IC based forecast was able to indicate correct sign of the observed rainfall anomaly (Fig. 6). The model forecasts based on February and April ICs were successful in predicting the sign of rainfall anomalies during all the recent three deficient monsoon years (2009, 2014 and 2015), according to Pai et al. (2017).

India experiences hot (cold) weather primarily during March to June (November to February) with many parts of the country experiencing heat (cold) wave conditions with many adverse consequences. The issue of seasonal outlook for sub-divisional average temperatures (maximum and minimum) over the country was introduced for the summer season of April to June and cold season of December to February based on MMCFS predictions from 2016 onwards, and seasonal temperature outlooks for March to May from 2017 onwards.

5. Concluding Remarks

Under the MM Programme, significant advances in operational weather and climate forecasting have been achieved by IMD due to improvement and augmentation of dynamical NWP and climate models. Improved warnings with increased accuracy and high lead period against hazards like cyclones, heavy rainfall and heat wave have helped disaster managers and general public to minimize loss of lives and property. However, there is still scope for improvement in terms of (i) better prediction of meso-scale hazards (like thunderstorm, hailstorm, squall etc.) detection and monitoring; (ii) increased spatial and temporal resolution of forecasts up to block/village level in short to medium range, up to district level in extended range time scale and up to state/level in monthly and seasonal timescales. All these aspects are being addressed now in the ongoing and subsequent phases of the Monsoon Mission.

References

Ashrit, R. et al., 2012: Performance of global ensemble forecast system (GEFS) during monsoon, NCMRWF report, NMRF/RR/1/2013. https://www.ncmrwf.gov.in/GEFS_Report_Final.pdf

Chattopadhyay, N. et al., 2018: Usability of extended range and seasonal weather forecast in Indian agriculture. *Mausam*, 69, 29-44.

Deshpande, M. et al., 2020: Implementation of Global Ensemble Forecast System (GEFS) at 12 km Resolution. Technical Report No. TR-06, 1-21, ESSO/IITM/MM/TR/02(2020)/200, ISSN 0252-1075, https://www.tropmet.res.in/~lip/Publication/Technical-Reports/TR-6.pdf.

Ganesh, S. et al., 2019: Genesis and track prediction of pre-monsoon cyclonic storms over North Indian Ocean in a multi-model ensemble framework. *Natural Hazards*, 95, 823-843, https://doi.org/10.1007/s11069-018-3522-6.

Gadgil, S. and Gadgil, S., 2006: The Indian Monsoon, GDP and Agriculture. *Economic and Political Weekly*, 41(47), 4887-4895, http://www.jstor.org/stable/4418949.

Hawkins, E. et al., 2013: Calibration and bias correction of climate projections for crop modelling: an idealised case study over Europe. *Agricultural and Forest Meteorology*, 170, 19-31.

Joseph, S. et al., 2019: Skill evaluation of extended range forecasts of rainfall and temperature over the meteorological subdivisions of India. *Weather and Forecasting*. 34, 81-101, https://doi.org/10.1175/WAF-D-18-0055.1.

Mandal, R. et al., 2019: Real time extended range prediction of heat waves over India. *Scientific Reports*, **9**, 9008, https://doi.org/10.1038/s41598-019-45430-6.

Mohapatra, M. and Sharma, M., 2019: Cyclone Warning Services in India during recent years: A review, *Mausam*, 70, 4, 635-666.

Mohapatra, M. et al., 2020: Evaluation of heavy rainfall warnings of India National Weather Forecasting Service for monsoon season (2002-18), *Journal of Earth System Science* (Accepted).

Mukhopadhyay P. et al., 2019: Performance of a very high-resolution global forecast system model (GFS T1534) at 12.5 km over the Indian region during the 2016-2017 monsoon seasons, *Journal of Earth System Science*, 128, 155, https://doi.org/10.1007/s12040-019-1186-6.

Pai D.S. et al., 2017: Performance of the operational and experimental long-range forecasts for the 2015 southwest monsoon rainfall, *Current Science*, 112, 68-75.

Parthasarathy, B., Munot, A.A. and Kothawale, D.R., 1988: Regression model for estimation of Indian food grain production from Indian summer rainfall, *Agricultural and Forest Meteorology*, 42, 167-182.

Rajeevan, M.N. et al., 2007: New Statistical models for long-range forecasting of southwest monsoon rainfall over India, *Climate Dynamics*, 28, 813-828.

Ramu, D.A. et al., 2017: Prediction of seasonal summer monsoon rainfall over homogenous regions of India using dynamical prediction system, Journal of Hydrology, Vol: 546, Page: 103-112, doi: 10.1016/j.jhydrol.2017.01.010

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Amer. Meteor. Soc.*, 100, 2509-2532, https://doi.org/10.1175/BAMS-D-17-0330.1.

RSMC New Delhi, 2020: Report on cyclonic disturbances over the North Indian Ocean during 2019, No. MOES/IMD/RSMC-Tropical Cyclone Report No/01(2020)/10, IMD, New Delhi, http://www.rsmcnewdelhi.imd.gov.in/images/pdf/publications/annual-rsmc-report/rsmc-2019.pdf.

Sahai, A.K. et al., 2020: Development of a probabilistic early health warning system based on meteorological parameters. *Scientific Reports*, https://doi.org/10.1038/s41598-020-71668-6

Sahai, A.K. et al., 2019: Seamless prediction of monsoon onset and active/break Phases. In: Sub-Seasonal to Seasonal Prediction, A.W. Robertson and F. Vitart, Eds., Elsevier, Chapter 20, 421-438.

Sen Roy, S. et al., 2019: A review of Nowcasting of convective weather over the Indian region, *Mausam*, 70, 465-484.

Monsoon Mission Societal Applications: Agriculture, Water, Health and Energy

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1. Background

The extended range prediction (ERP) that falls in between the seasonal and short-range time scales is a vital component of the "Monsoon Mission" program (Rao et al., 2020) initiated by the Ministry of Earth Sciences (MoES), Government of India in 2011. It aims to provide an outlook on the state of atmosphere beyond one week to a maximum of 4 weeks. Although seasonal prediction gives an overview of an upcoming monsoon season, the prediction of sub-seasonal fluctuations of rainfall within the monsoon season with a lead time of 2-3 weeks is essential in the view of agricultural and hydrological planning. Additionally, the ERP of temperature fluctuations during the summer and winter months is useful in the health, energy and agricultural sectors (Joseph et al., 2019). The forecasts can be beneficial in insurance, reinsurance, infrastructure, transportation and urban planning sectors as well.

The ERP system developed by the Indian Institute of Tropical Meteorology (IITM) consists of four variants of the Climate Forecast System version 2 (CFSv2) model of National Centre for Environmental Prediction (NCEP), USA (Sahai et al., 2019). The various forecast products generated from this ERP system include ERP of onset phase, active-break spells and withdrawal phase of the Indian summer monsoon, monitoring of monsoon intraseasonal oscillations (MISOs) and Madden-Julian Oscillation (MJO), fluctuations in northeast monsoon and extreme events like heavy rainfall events, heat and cold waves and tropical cyclogenesis (Abhilash et al., 2014, 2015; Dey et al., 2020; Ganesh et al., 2018, 2019; Joseph et al., 2015a,b; Mandal et al., 2019). The prediction system is found to be skillful in predicting the rainfall and temperature fluctuations in different seasons (Joseph et al., 2019).

Considering its reasonable skill and wide range of applications, the ERP system developed under the "Monsoon Mission" has been transferred to India Meteorological Department (IMD), the national weather forecasting agency, and has been fully operational since July 2016.

2. Societal applications of ERP

Extremes of temperature and rainfall are known to have broad and far-reaching impacts such as significant loss of life, health issues, and increased economic costs in transportation, agricultural production, energy and infrastructure. Hence, a timely and accurate forecasts can facilitate decision making to alleviate the adverse effects to a great extent. Some initiatives to apply ERP capabilities developed under the Monsoon Mission to support societal applications in key areas are briefly outlined in the following paragraphs.

Agricuture: The ERP of wet, dry, hot, cold, windy and humid conditions has a lot of applications in the agricultural sector in planning the optimal time for sowing, irrigation, pest control and harvesting. The present ERP system is used by IMD to generate National Agromet Advisory Service Bulletins every week (available at http://www.cropweatheroutlook.in/crida/amis/contingencyPlan/NAAS.jsp) and these forecasts are found to be useful in strategic planning of farm operations (Chattopadhyay et al., 2018). The calibrated ERP forecasts were used in four selected districs of Bihar during 2018 (Robertson et al., 2019). There is an encouraging feedback from the farmers on the forecasts, and work is in progress to evaluate the benefit of the forecasts issued during the pilot project in economic terms.

Hydrology: ERP of the rainfall in a river catchment area and the duration and intensity of hot/dry spells would be helpful for dam managers to decide on the amount of water to be held in or released from the dams to minimize the risks of floods or water shortage (Sahai et al., 2017). The hydrologic prediction based on the ERP data and the Variable Infiltration Capacity (VIC) model can provide a basis for predicting both meteorological and hydrological anomalies and the information can be provided to farmers and water managers. The forecast of root-zone soil moisture along with precipitation and temperature anomalies can be used for irrigation planning. Moreover, skillful runoff forecast (Fig. 1) at the 7-45-day accumulation period can be valuable for water managers in India (Shah et al., 2017); also see: https://sites.google.com/iitgn.ac.in/expforecastlandsurfaceproducts/erf-weekly-forecast-cumulative/weekly-runoff.

Furthermore, an effort has been made to compute various drought indices such as the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) and Palmer Drought Severity Index (PDSI) using ERP forecasts (Shrivastava et al., 2018) and it was found that the probabilistic forecasts and the drought indices from the prediction system are quite useful to identify droughts over central India 20 days in advance. Another example for the utilization of ERP products is the South Asia Drought Monitoring System (SADMS) drought weekly bulletin produced by the International Water Management Institute (IWMI) to support Governments and users. This bulletin is available at:

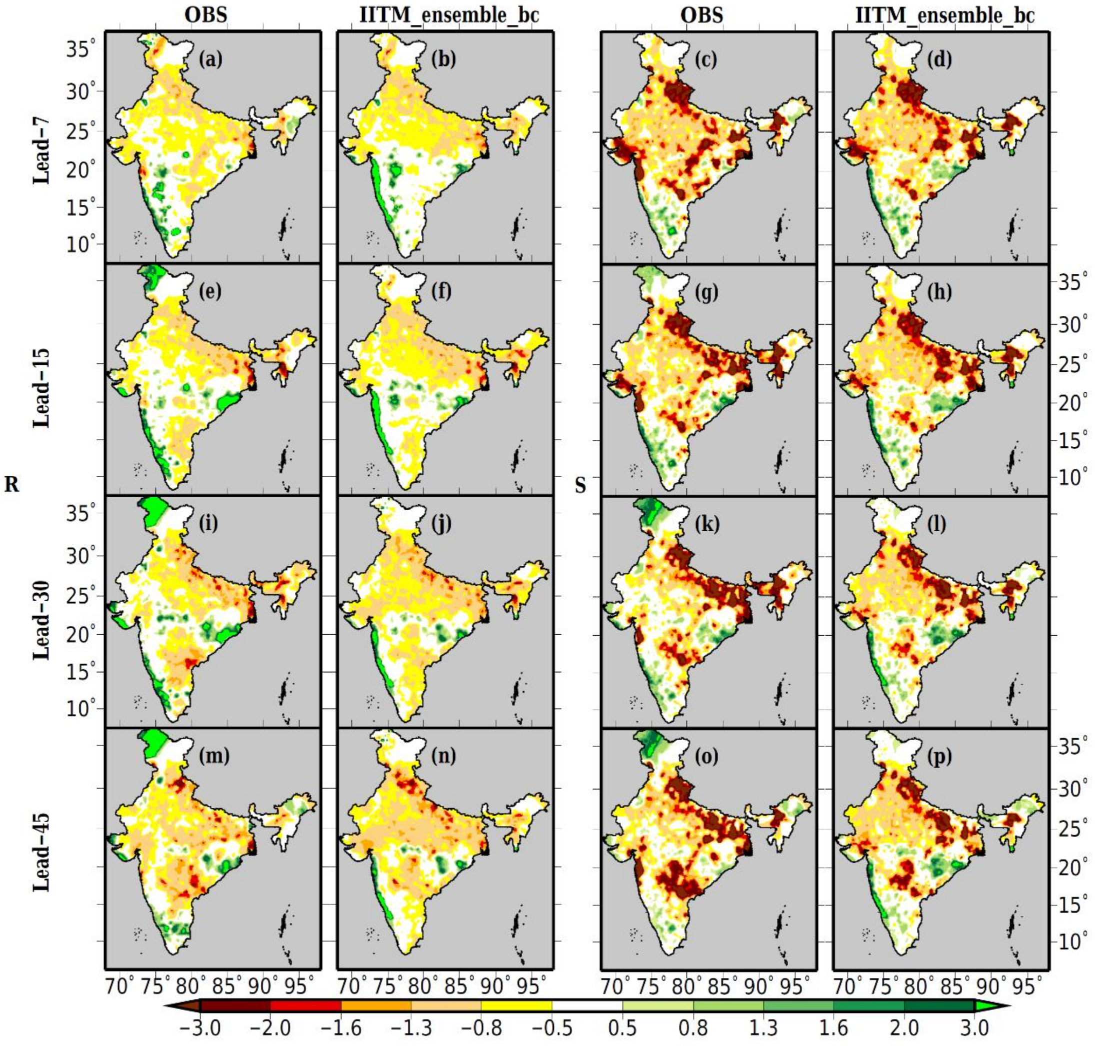

Fig. 1: Predicted anomalies of hydrologic variables for the forecast initiated on 15 July 2009 for the accumulation periods of 7, 15, 30, and 45 days. (a) Observed (standardized) anomalies in (VIC-simulated) runoff at a lead time of 7 days. (b) Anomalies in (VIC-simulated) runoff using the bias corrected IITM ensemble for the accumulation period of 7 days. (c, d) Same as (a, b) but for root-zone soil moisture. (e–p) Same as (a)-(d) but for the accumulation periods of 15, 30, and 45 days, respectively (adapted from Shah et al., 2017).

https://www.iwmi.cgiar.org/resources/drought-monitoring-system/drought-bulletin/.

Disaster management: Cyclonic storms are among the most devastating weather phenomena that pose threat to life and property because of the strong winds, heavy rains and storm surges associated with them. The ERP of the genesis and evolution of cyclonic systems would serve as guidance to the disaster management authority to reduce the gravity of damage (Ganesh et al., 2018, 2019). The early warning on impending heavy rainfall events given by the ERP system (Joseph et al., 2015) can improve the preparedness of disaster management authority so that the loss to life and property can be averted to a great extent.

Health: Weather parameters like temperature, rainfall and humidity can directly or indirectly affect the incidence of vector-borne diseases (Sahai et al., 2020). In addition, the abnormal high and low temperatures can cause thermal stress to humans and livestock, leading to severe health problems and even threat to their life. Based on the extended range forecast disseminated every week, health advisories for the transmission of vector-borne diseases are generated by IMD on a regular basis. Recently, an early health warning system has been developed by nonlinear clustering of weather parameters from the ERP outputs (Sahai et al., 2020), and initial results suggest that the system has promising skill (Fig. 2).

Energy: The energy sector significantly depends on the weather and climate, which impacts demand and supply (Dubus et al., 2018). If it is too hot or cold outside, the power consumption increases, and the energy providers must ensure the availability of this extra power at the right time. Therefore, ERP of extreme temperatures can contribute to the preparedness in the energy sector. An outlook on impending heavy rainfall events, storms etc also help them to manage the resources wisely.

Urban Planning: Urban planning is closely interlaced with the climatic conditions of a particular area. The urban climatic issues of heat, humidity, lack of daylight, solar access, and urban ventilation is of topical concern to urban planners and governments. It is important for planners and architects to understand the “prevailing” and “critical” climatic conditions over the region before planning any type of construction

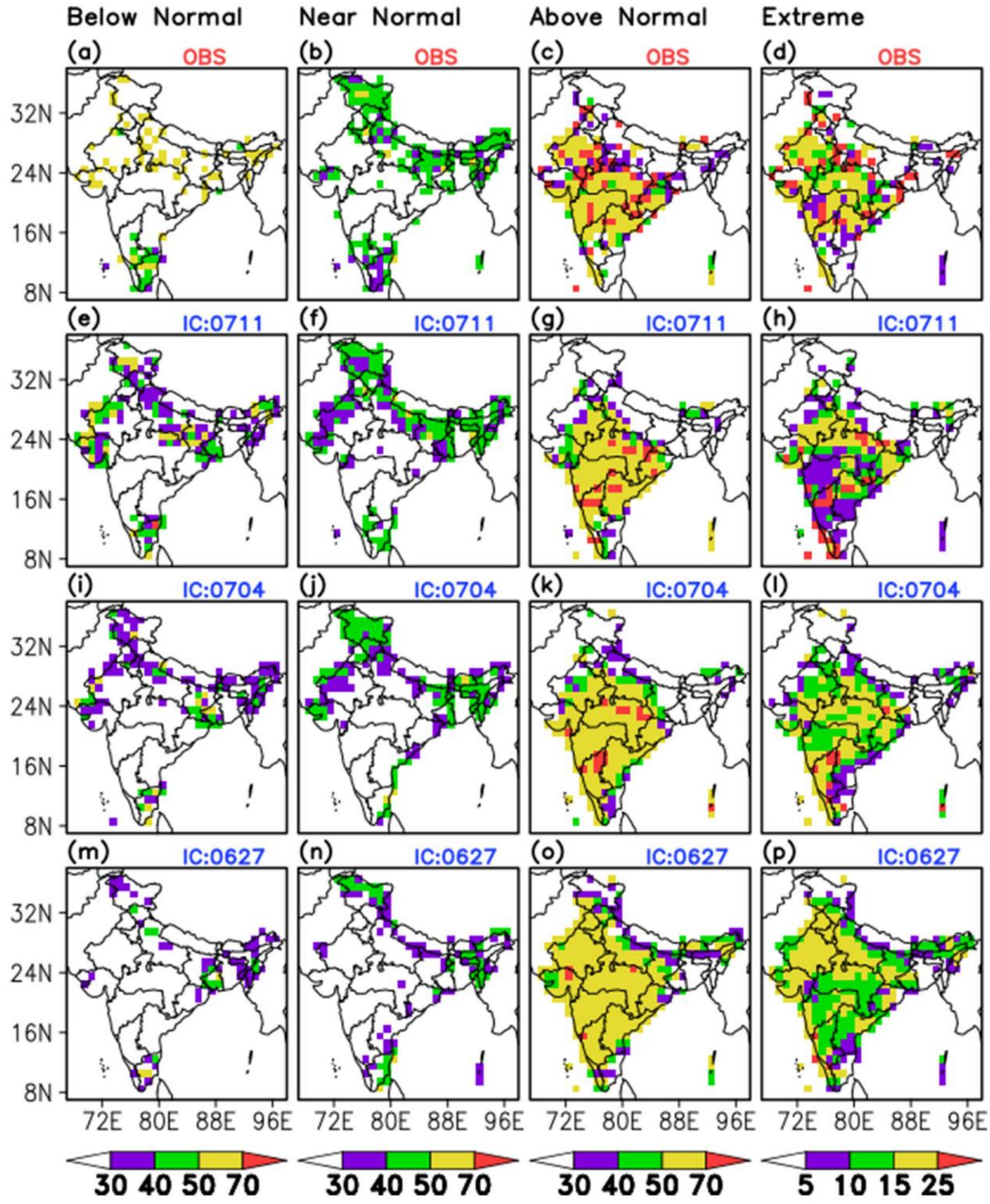

Fig. 2: Probabilities of below normal, near normal, above normal and extreme category of occurrences of malaria during 12-18 July 2018 for observation (a-d) and forecasts from initial conditions 11 July (e-h), 4 July (i-l) and 27 June 2018 (m-p) (adapted from Sahai et al., 2020).

work (Ng, 2012). The ERP on impending dry/wet spells can be very useful for the district administration to plan the timing for road repair works and other construction works to ensure the prevalence of favourable weather conditions during their work period. ERP can be useful for urban planning as acknowledged for Pune city for a specific use case.

Fisheries: In a recent initiative, the ERP data are being used to drive the ocean biogeochemistry modules to produce certain valuable marine ecosystem variables (Sreeush et al., 2017). A few examples are forecasting and monitoring surface ocean partial pressure of dissolved CO_2 gas (pCO_2), sea-to-air CO_2 fluxes, surface ocean pH, primary productivity, new production, export production, etc. The forecasting and monitoring of surface ocean pH have great marine environmental value as it could be used as an indicator of potential fishery zones. Localized patches of extreme acidification are noticed in global surface oceans lasting for a week to a few tens of days. ERP related ocean data products can be rightfully utilized to derive such biogeochemistry variables with potential applications in marine ecosystem modeling and monitoring. The work of developing biogeochemistry data products from the ERP system is underway.

3. Short-range forecast system for wind and solar energy applications

There is now a major focus on renewable energy sources globally in general and over India in particular, to meet the increased demands for energy in a sustainable and eco-

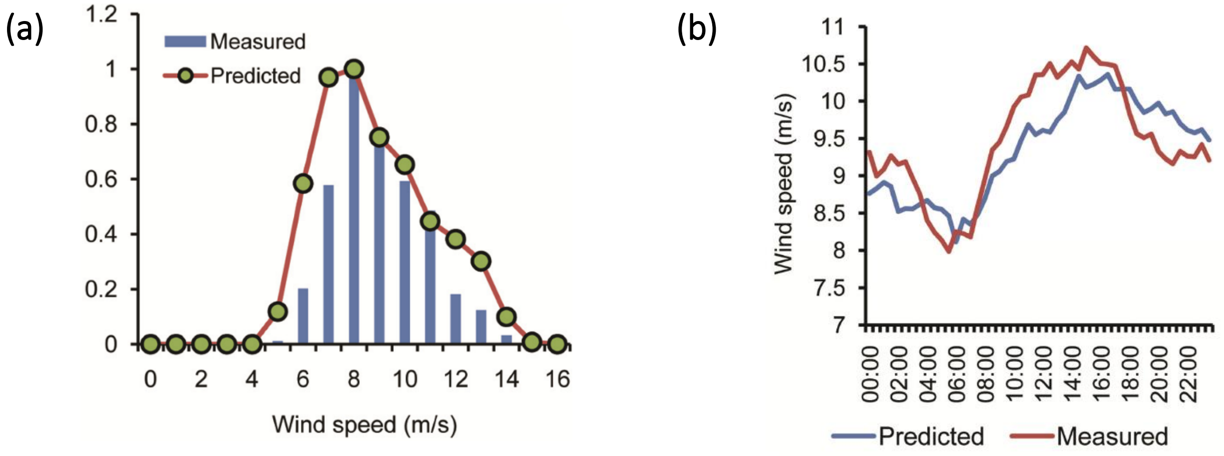

Fig. 3: (a) Probability density function of wind speed at Haikaal, Karnataka, India during August 2016; (b) Average diurnal cycle at Haikaal, Karnataka during July 2016 (adapted from Gangopadhyay et al., 2019).

friendly manner. Renewable energy resources include wind, hydropower, biomass and solar energy. In India the solar power has the highest potential of 68% followed by wind power potential ~28% (Kanase et al., 2020). To exploit the solar and wind energy potential, the stakeholders are in need of accurate forecasts from the meteorological community about a day in advance (24-hour lead time) of the wind at around 100 m height and also the shortwave incoming solar radiation at the surface. As per the requirements specified by the Ministry of Non-conventional and Renewable Energy, Government of India, the wind forecast needs to be provided at every 15 minutes.

To take the above societal needs into account, an initiative was taken up at IITM to set up a forecasting system applicable for any wind and solar site in India (Kanase et al., 2020). For the purpose of forecast demonstration, the forecasting system was tested in a few sites of Maharashtra state, India. The output of the forecasting system has also been evaluated against wind observations of another state Karanataka, to be used to identify regions with high wind speed. The evaluation results (Gangopadhyay et al., 2019) reveal that the forecasting model is able to capture the probability density function and the diurnal cycle of the wind over the station reasonably well (Fig. 3).

The forecasting system includes state-of-the art global forecast system (GFS) at 12 km resolution adopted from NCEP, USA under the Monsoon Mission programme and further downscaling to 1 km resolution by mesoscale model (WRF) (Gangopadhyay et al., 2019; Kanase et al., 2020). The wind and solar forecasts are further bias corrected from the observations available at the wind and solar sites. Based on the initial success of the wind and solar forecasts at different sites in India, GFS forecast downscaled at 3km resolution has routinely been shared with stakeholders including government agencies (e.g., Power System Operation Corporation, https://posoco.in/) on experimental basis. The evaluations of wind and solar forecasts with observations and also by other forecasts are shown in Fig. 4. The IITM forecasts for both wind and solar parameters are found to perform reasonably well as compared to the observations.

The initiatives undertaken under the Monsoon Mission for wind and solar energy applications will be further enhanced under MoES programmes and the improved forecasts would be provided to the stakeholders for strengthening the wind and solar energy sectors.

References

Abhilash, S. et al., 2014: Does bias correction in the forecasted SST improve the extended range prediction skill of active-break spells of Indian summer monsoon rainfall? *Atmos. Sci. Lett.,* 15, 114-119, https://doi.org/10.1002/asl2.477.

Abhilash, S. et al., 2015: Improved Spread-Error Relationship and Probabilistic Prediction from the CFS-Based Grand Ensemble Prediction System, *J. Appl. Meteorol. Climatol.*, 54, 1569-1578, https://doi.org/10.1175/JAMC-D-14-0200.1.

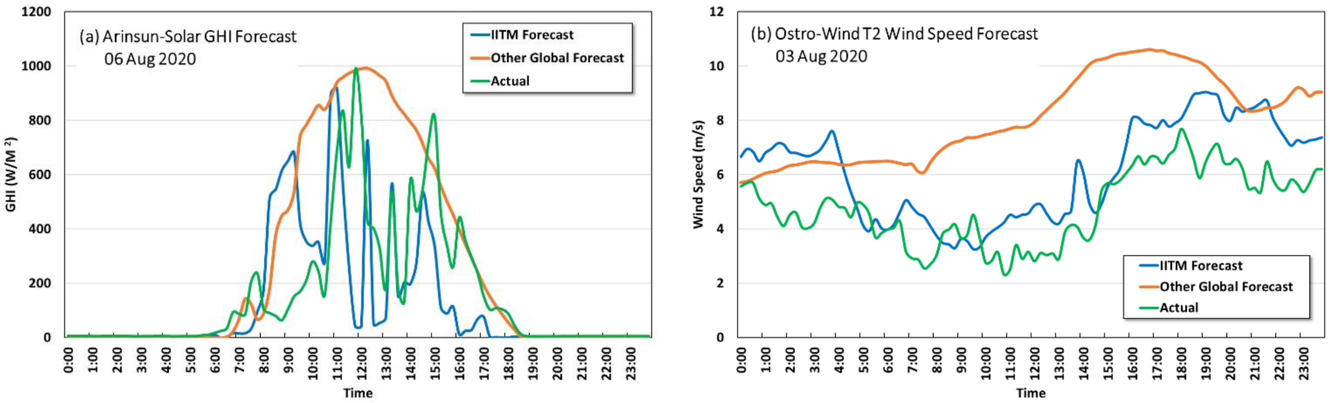

Fig. 4: Evaluation of IITM forecasts of (a) solar radiation (Global Horizontal Irradiance, GHI) for Arinsun-Solar on 6 August 2020 and (b) wind speed for Ostro-Wind on 3 August 2020.

Chattopadhyay, N. et al., 2018: Usability of extended range and seasonal weather forecast in Indian agriculture, *Mausam*, 69, 29-44.

Dey, A. et al., 2020: MJO Prediction Skill Using IITM Extended Range Prediction System and Comparison with ECMWF S2S, *Pure Appl. Geophys.*, 177, 5067-5079, https://doi.org/10.1007/s00024-020-02487-z.

Dubus, L., Muralidharan, S. and Troccoli A., 2018: What Does the Energy Industry Require from Meteorology?. In: Troccoli A. (eds) Weather & Climate Services for the Energy Industry. Palgrave Macmillan, Cham, https://doi.org/10.1007/978-3-319-68418-5_4.

Ganesh, S.S. et al., 2019: Genesis and track prediction of pre-monsoon cyclonic storms over North Indian Ocean in a multi-model ensemble framework, *Natural Hazards*, 95, 823-843, https://doi.org/10.1007/s11069-018-3522-6.

Ganesh S.S. et al., 2018: New approach to improve the track prediction of Tropical cyclones over North Indian Ocean, *Geophys. Res. Lett.*, 45, 1-9, https://doi.org/10.1029/2018GL077650.

Gangopadhyay A. et al., 2019: Use of a weather forecast model to identify suitable sites for new wind power plants in Karnataka, *Current Science*, 117, 1347-1353, https://doi.org/10.18520/cs/v117/i8/1347-1353.

Joseph S. et al., 2015a: North Indian heavy rainfall event during June 2013: diagnostics and extended range prediction, *Climate Dynamics*, 44, 2049-2065, https://doi.org/10.1007/s00382-014-2291-5.

Joseph, S. et al., 2015b: Development and Evaluation of an Objective Criterion for the Real-Time Prediction of Indian Summer Monsoon Onset in a Coupled Model Framework. *J. Climate*, 28, 6234-6248, https://doi.org/10.1175/JCLI-D-14-00842.1.

Joseph, S. et al., 2019: Skill evaluation of extended range forecast of rainfall and temperature over meteorological subdivisions of India, *Weather and Forecasting*, 34, 81-101, https://doi.org/10.1175/WAF-D-18-0055.1.

Kanase, R. et al., 2020: Initiative to Develop a Forecasting System for Wind Energy over a complex terrain in India using Weather Research and Forecasting (WRF) Model, IITM RR-147, ISSN 0252-1075, 45pp, https://www.tropmet.res.in/~lip/Publication/RR-pdf/RR_147.pdf.

Mandal, R. et al., 2019: Real time extended range prediction of heat waves over India, *Scientific Reports*, 9, 9008, https://doi.org/10.1038/s41598-019-45430-6.

Ng, E., 2012: Towards planning and practical understanding of the need for meteorological and climatic information in the design of high-density cities: A case-based study of Hong Kong, *Int. J. Climatol.,* 32, 582-598, https://doi.org/10.1002/joc.2292.

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Amer. Meteorol. Soc.,* 100, 2509-2532, https://doi.org/10.1175/BAMS-D-17-0330.1.

Robertson A.W. et al., 2019: Subseasonal forecasts of the 2018 Indian Summer Monsoon over Bihar, J. Geophys. Res. (Atmospheres), 124, 13861-13875, https://doi.org/10.1029/2019JD031374.

Sahai A.K. et al., 2017: A bias‑correction and downscaling technique for operational extended range forecasts based on self-organizing map, *Climate Dynamics*, 48, 2437-2451, https://doi.org/10.1007/s00382-016-3214-4.

Sahai, A. K. et al., 2019: Seamless prediction of monsoon onset and active/break phases. In: Sub-Seasonal to Seasonal Prediction, A.W. Robertson and F. Vitart, Eds., Elsevier, Chapter 20, 421-438.

Sahai, A.K. et al., 2020: Development of a probabilistic early health warning system based on meteorological parameters, *Scientific Reports*, 10, 14741, https://doi.org/10.1038/s41598-020-71668-6.

Shah, R., Sahai, A. K. and Mishra, V., 2017: Short to sub-seasonal hydrological forecast to manage water and agricultural resources in India, *Hydrol. Earth Sys. Sci.*, 21, 707-720, https://doi.org/10.5194/hess-21-707-2017.

Shrivastava, S. et al., 2018: Identification of Drought Occurrences Using EnsemblePredictions up to 20-Days in Advance, *Water Resources Management*, 32, 2113-2130, https://doi.org/10.1007/s11269-018-1921-9.

Sreeush, M.G. et al., 2019: Biological production in the Indian Ocean upwelling zones - Part 2: Data based estimates of variable compensation depth for ocean carbon models via cyclo-stationary Bayesian Inversion, *Deep Sea Research Part II, In Press*, https://doi.org/10.1016/j.dsr2.2019.07.007.

Advances in Coupled Data Assimilation, Ensemble Forecasting, and Assimilation of Altimeter Observations

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1. Introduction

Indian economy is strongly linked to agricultural production, which is critically dependent on the summer monsoon rainfall during June to September. Seasonal and extended range prediction of Indian summer monsoon has been a challenging task for meteorological communities. A better forecast of the monsoon will aid the government in taking precautionary measures to tackle issues like deficits in food production, damage due to floods, etc. The prediction of the inter-annual, seasonal and sub-seasonal variation of the Indian summer monsoon rainfall, particularly for the occurrence of extreme events like droughts and excessive rainfall is highly important. Monsoon intra-seasonal oscillations (MISOs) are features of the precipitation which have been shown to be predictable for many months but not forecasted well by current models (Krishnamurthy and Sharma, 2017; Mandke et al., 2020). This article briefly outlines some of the new initiatives, under Monsoon Mission (MM) Programme Phase II (MM-II), to improve model performance including through innovative assimilation approaches.

2. A new Weakly Coupled Data Assimilation system

The predictions from coupled models are highly sensitive to the errors in initial conditions (Balmaseda et al., 2009; Balmaseda and Anderson, 2009). With the purpose of improving the accuracy of ocean and atmospheric initial conditions, an ensemble-based flow-dependent data assimilation system was developed under MM-I (Rao et al., 2019) and substantially improved in the MM-II. In this section we present an evaluation of the results.

The 4D-Var assimilation method, although advanced, has the difficulty of implementing the tangent linear and adjoint models when the general circulation models are frequently updated, while simpler schemes like 3D-Var and Optimal Interpolation miss the "errors of the day". By contrast, the Local Ensemble Transform Kalman Filter (LETKF) uses time-evolving background error covariances (Sluka et al., 2016) without the need of the tangent linear and adjoint models. We adopt the method of Weakly Coupled Data Assimilation (WCDA), where the observations from independent domains (ocean and atmosphere) are used for assimilation only in their respective domains.

A weakly coupled ocean-atmosphere Climate Forecast System (CFS)-LETKF Data Assimilation system was developed by the University of Maryland (UMD) during MM-I. Like its predecessor from CFSv2 of the National Centres for Environmental Prediction (NCEP), it incorporated sea surface temperature (SST) information using nudging, which is not accurate enough, as shown in Fig. 1. The SST nudging was turned off, with the intention of replacing it with a more accurate assimilation of SST observations (L2). But MM-I ended before this could happen. After the start of MM-II the UMD team became aware of the lack of SST information and considered what would be the most accurate replacement of the SST nudging.

Two methods were implemented into the CFS-LETKF, one assimilating Level 2 (L2) surface temperature observations, and the other using observations from Level 4 (L4) high resolution and quality-controlled SST Reanalyses. A CFS-LETKF User Guide was developed by UMD and shared with IITM, which included the observation operator for L2 observations, as well as that for using an L4 SST analysis, as an example applicable to any SST reanalysis. IITM adopted the NOAA-SST Reanalysis L4 observations, described in Maturi et al. (2017).

This paper highlights some encouraging results from this advanced IITM-UMD CFS-LETKF system. The ocean model component is MOM4p1 coupled with LETKF, and the atmospheric component is GFS coupled with LETKF. The ocean observations assimilated are the global vertical profiles of temperature and salinity (obtained from the Indian National Centre for Ocean Information Services, INCOIS) and global high-resolution satellite-derived blended SST (Maturi et al., 2017). The atmospheric variables assimilated are surface pressure, temperature, humidity, and horizontal winds (obtained from NCEP PrepBUFR, i.e., no radiance observations). The initial ensemble members are created from 40 realizations of January 1st and 2nd of years in the period 1979 to 2011 using CFS Reanalysis (CFSR), and the

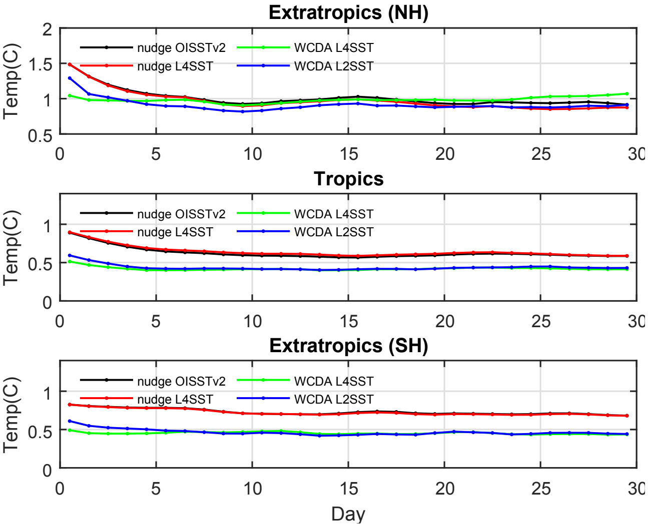

Fig. 1: The time series of the RMSE of the mean SST analysis for nudge OISSTv2 (black), nudge L4SST (red), WCDA L4SST (green), and WCDA L2SST (blue) in the region of extratropics in the Northern Hemisphere (upper panel), the tropics (middle), and the extratropics in the South Hemisphere (bottom panel)

system is spun up for one year (2002). Ensembles of both ocean and atmospheric analyses have been created at 6-hour intervals for the period 2003-2009.

The operational seasonal and extended range predictions of monsoon using CFSv2 have been using the 3D-Var based oceanic initial conditions (INCOIS Global Ocean Data Assimilation System, GODAS). Here we have compared the nature of flow-dependent WCDA LETKF oceanic analysis with INCOIS GODAS. The resolution of the ocean model (0.25° at tropics, gradually relaxed to 0.5° at poles) is the same for both INCOIS GODAS and IITM-UMD WCDA. Fig. 2 shows the analysis error (bias) and Root Mean Square Error (RMSE) in surface (15m) zonal current for IITM-UMD WCDA and INCOIS GODAS. Here the truth considered is Ocean Surface Current Analysis Real-time (OSCAR) currents at 15m depth. The INCOIS GODAS has large errors in zonal currents especially in the equatorial regions of the world oceans. The analysis errors have been significantly reduced in CFS-LETKF ocean analysis compared to INCOIS GODAS. The RMSE is also improved in IITM-UMD WCDA.

The atmospheric analysis of IITM-UMD CFS-LETKF (T126, ~108 km) also shows improvements in the precipitation and relative humidity, when compared to the higher resolution ERA-Interim (T255, ~80km) atmospheric analysis. The precipitation analysis of the CFS-LETKF showed improvements in RMSE compared to ERA-INTERIM analysis (T255, ~80 km) as shown in Fig. 3, except in the West Coast where the IITM-UMD system is too dry.

3. CFS-LETKF: Impact of assimilating SST observations compared to SST Nudging

To compare the impact of SST observations assimilation with nudging, experiments were carried out at UMD, using the CFSv2-LETKF with a WCDA and SST nudging. Experiments with nudging/data assimilation (DA) cyclings are from June 1 to 30, 2020 with a 6-hr assimilation window in the atmosphere and 1 day in the ocean. All experiments are initialized from coupled CFS-LETKF analyses provided by IITM. The 10-day forecasts are initialized from the analysis generated by DA/nudging experiments at 12Z from June 15 to 19, 2020. The forecast evaluation is presented as a statistical mean of the forecasts started from the 5 different initial times. The results are verified against ERA5 reanalysis SST and the ocean temperature profile from the World Ocean Database. We found that WCDA gives superior SST and mixed layer subsurface temperature analyses (Fig. 1) as well as improved forecasts (not shown), compared to nudging, particularly in the tropics and SH. We also found that WCDA spins up faster than nudging. The monthly mean SST analysis shows significant improvements with assimilation of either L2 or L4 SST observations. The assimilation of SSTs significantly reduces the SST warm bias near the equator and Indian Ocean. For nudging, the ocean state would only be adjusted during the model integration. In contrast, WCDA can improve the ocean state from both model integration and the assimilation, in which the corrections can be introduced depending on the error correlations in the background error covariance. Thus, the observation information from the surface measurements can vertically spread to deeper layers and lead to significant improvements at the deeper layer. These improvements in the ocean further result in significant reduction in the atmosphere forecast RMSE of humidity, temperature and the horizontal winds.

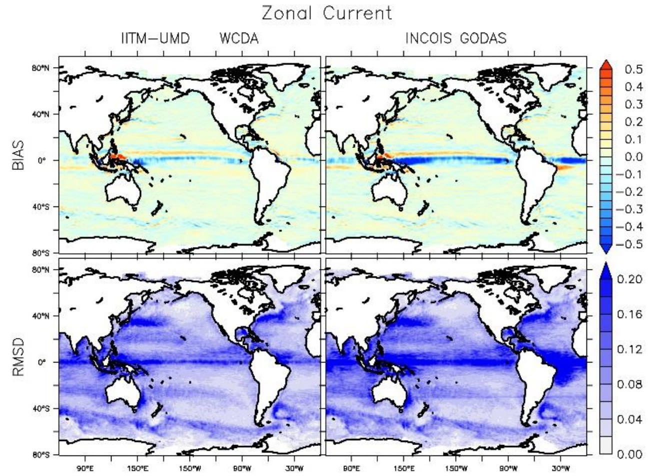

Fig. 2: Analysis error (bias) in the zonal current (m/sec) at 15 m depth, for a) IITM-UMD CFS-LETKF, b) INCOIS GODAS; Lower panels represent RMSE (m/sec); analysis period 2003 to 2009. For truth we considered the OSCAR currents at 15m

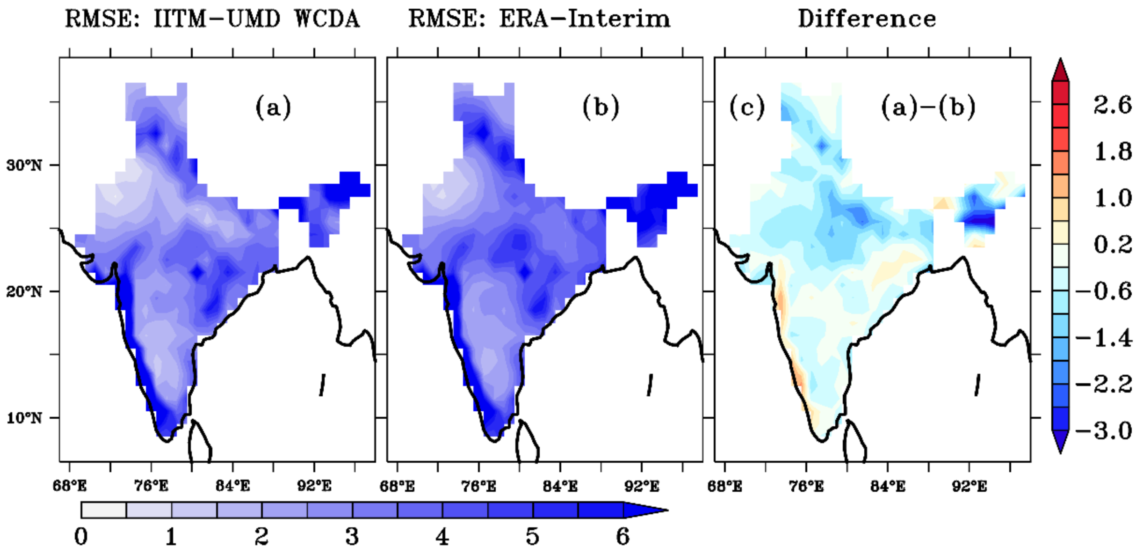

Fig. 3: RMSE in the analysis of precipitation (mm/day) for (a) IITM-UMD WCDA (T126, ~108km); (b) ERA-Interim (T255, ~80km); (c) Difference in RMSE (IITM-UMD WCDA *minus* ERA-Interim). Analysis period: 2003-2009; truth considered: IMD gridded rainfall data.

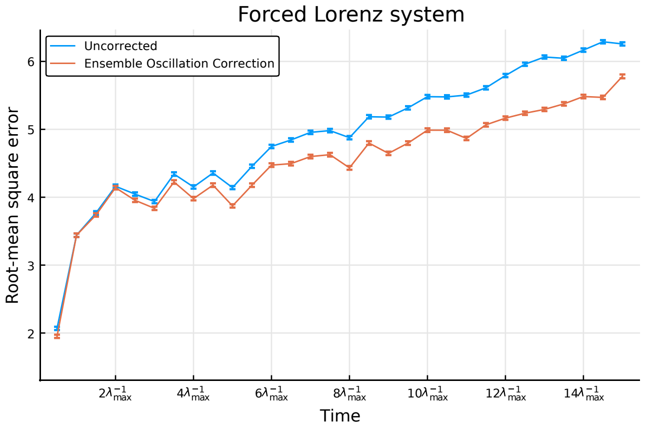

Fig. 4: The root-mean-square error of forecasts of the periodically forced Lorenz '63 system as a function of lead time, comparing the uncorrected forecast and the EnOC forecast.

4. Effective assimilation of altimeter observations

Effective assimilation of altimetry observations such as sea level anomaly (SLA) with the ensemble Kalman filter (EnKF) is challenging for three reasons. First, the SLA observations, which are the focus of several past studies and calculated by removing the mean dynamic topography (MDT) from the retrieved altimetry absolute dynamic topography (ADT), are highly dependent on the selection of the MDT (Martin et al., 2015). In addition, assimilating nonlocal observations such as altimetry observations in the EnKF is nontrivial due to the ambiguity of setting their vertical locations for the observation localization (Houtekamer and Zhang, 2016). Removal of the vertical localization causes degraded analyses in the deep ocean due to the sampling errors arising from the small ensemble size (see Fig. 4). Finally, the bias needs to be corrected whether it comes from the altimetry observations or their simulations, to prevent biased analysis increments (Keppenne et al., 2005; Lea et al., 2008; Sandery et al., 2020).

In this project, we investigated the impact of assimilating *directly* the altimetry ADT observations, rather than the SLA. We also added a new localization strategy: we only assimilate those observations which have high correlations with every model variable, since the EnKF underestimates small correlations more severely than high correlations (we call this method the **correlation threshold method**). This method automatically sets the localization depth of ADT observations at the level with the maximum state-observation correlation, so ADT observations are effectively localized at different levels for different model variables (i.e., temperature, salinity, and U/V-currents). Unlike the isotropic distance-based localization function, this method generates anisotropic localization, which should be more suitable for velocity updates based on the geostrophic balance. For comparison, we performed two other experiments with alternative strategies: 1) we assimilated ADT observations with no vertical localization, and 2) We vertically localized those observations at the level with the maximum temperature spread, considered to be a proxy of the thermocline depth, where they are supposed to have the most significant impact.

With the CFS-LETKF, we conducted experiments from June 1 to June 19 in 2006 with different localization strategies for the ADT assimilation, as well as a control experiment without ADT assimilation. The initial 40 members were from the IITM's CFS-LETKF analysis on June 1 in 2006. The T126 (~1°) atmospheric component assimilates PrepBUFR (conventional, not radiance observations) every 6 hours while the 0.5° oceanic counterpart assimilates the ADT superobs from Jason-1, Envisat, and GFO every 24 hours. A simple online constant bias correction was applied to the ADT assimilation to remove the positive bias in each assimilation cycle.

The verification of the analyses against independent ocean profiles during the same period (Fig. 5) shows that without vertical localization (Fig. 5a), the ocean temperature and salinity analyses in the top 900m are improved, but that the assimilation of ADT observations degrades the analyses globally in the deeper layers. Localizing the ADT observations near the level with maximum temperature spread (Fig. 5b) reduces the positive impact on the top 500m in the ocean and causes degraded temperature and salinity analysis in the Southern Hemisphere. By contrast, the temperature and salinity analysis obtained with the **correlation threshold method** show reduced RMSE in the top 900m with no degradation in the deeper layers. Also, the most substantial temperature improvements take place at a shallow level in the tropics (TR) while they appear in a deeper layer in the Northern Hemisphere (NH), and are absent in the Southern Hemisphere (SH), all of which are consistent with what we should expect from ocean dynamics. Given these consistently positive results, we will evaluate the long-term performance

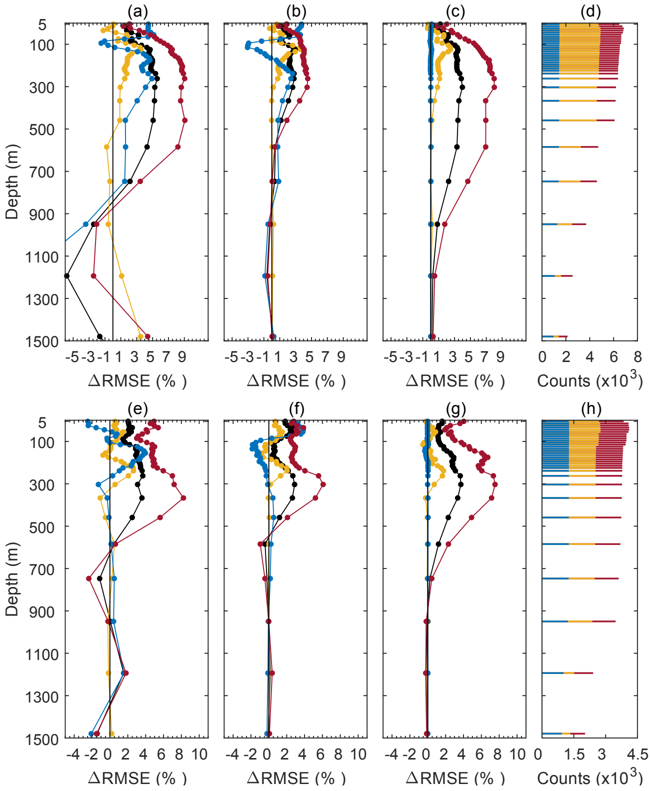

Fig. 5: RMSE reduction (%) of the temperature (top row) and salinity (bottom row) analyses in the SH (blue), TR (yellow), NH (red) and the globe (black) by the ADT observations without vertical localization (1st column), with vertical localization at the level with the maximum temperature spread (2nd column), and with localization determined from the correlation threshold method (3rd column). The number of observations for verifications are shown in the 4th column.

of this new localization method by extending our experiments and assessing its influence on ocean forecasts.

5. Leveraging oscillatory modes to improve ensemble forecasts, with future application to MISOs

MISOs consist of northward propagating rainfall patterns, whose origin is not yet fully understood. The MISOs characterize the active and break phases of the monsoon, and much of regional rainfall patterns. Accurate forecasts of regional rainfall, rather than just the seasonal mean rainfall, are crucial for the agricultural and hydrological sectors (Krishnamurthy and Shukla, 2007; Xavier and Goswami, 2007).

However, current state-of-the-art dynamical models often poorly predict the MISOs (Mandke et al., 2020). Krishnamurthy and Sharma (2017), using a data-driven MISO forecasting method, demonstrated MISO predictability for up to 80 days. This demonstrates the potential for improved intraseasonal prediction of monsoon rainfall. In fact, oscillations in the climate system (such as MISOs), due to their near-regularity, are recognized as an important source of predictability in the climate system beyond the weather time scale (Krishnamurthy, 2019).

While methods such as the one in Krishnamurthy and Sharma (2017) have been developed for data-driven prediction of MISO, the major obstacle in using these predictions to improve overall forecasts is that MISOs alone comprise only a portion of the variance of the rainfall over the Indian subcontinent. There has not previously been a method for leveraging the forecast of these oscillations in order to improve the overall forecast. We developed a novel method, *Ensemble Oscillation Correction (EnOC)*, to beneficially combine data-driven forecasts of oscillations with an ensemble of dynamical forecasts of the full system. Although we are here interested in the Indian monsoon, this method could be used with any system that possesses significant oscillatory components.

We give a brief overview of EnOC; the technical details can be found in Bach et al. (2020). First, using a historical time-series of the system, we use a method called multi-channel singular spectrum analysis (Ghil et al., 2002) to extract the oscillation of interest, yielding a time-series of the oscillation. This oscillation time-series allows us to forecast the oscillations at future times using an analog method. For real-time forecasting of the system, we assume we have an ensemble of forecasts up to some lead time. We then compute the ensemble mean using only the best ensemble members, as defined by their discrepancy from the data-driven forecast of the oscillation. We also developed an alternate method, *Ensemble Oscillation Correction with Data Assimilation (EnOC-DA)*, which uses data assimilation to combine the data-driven oscillation forecasts with the dynamical forecasts of the full system.

So far, we have tested this method with toy chaotic models which possess oscillatory components; this is meant to serve as a simple analog of the Indian monsoon. EnOC and EnOC-DA exhibit robust error reductions compared to uncorrected ensemble forecasts (see Fig. 5 for an example). These positive results on toy models suggest EnOC's applicability to the Indian monsoon, which is the next phase of the project.

Another approach to incorporate the MISO forecasts in the DA is "Running in Place" (RIP) (Kalnay and Yang, 2010), where the No-Cost Ensemble Kalman Smoother is applied, and the (MISO) observations are used more than once in each assimilation window to maximize the extraction of MISO information. Chang et al. (2021) tested RIP on the same toy models with similar encouraging results.

References

Bach, E. et al., 2020: Ensemble Oscillation Correction (EnOC): Leveraging oscillatory modes to improve forecasts of chaotic systems (*in preparation*).

Balmaseda, B.A., et al., 2009: Ocean Initialization for Seasonal Forecasts, *Oceanography*, 22, 3, 154-159.

Balmaseda, M.A. and Anderson, D., 2009: Impact of initialization strategies and observations on seasonal forecast skill, Geophys. Res. Lett., 36, L01701, doi:10.1029/2008GL035561.

Chang, C.-C., E. Bach and E. Kalnay, 2021: Handling oscillating forcing in a chaotic system with advanced ensemble data assimilation approaches (*in preparation*).

Ghil, M. et al., 2002: Advanced Spectral Methods for Climatic Time Series. *Rev. Geophys.*, *40*(1), 3-1-3-41.

Houtekamer, P.L. and Zhang, F., 2016: Review of the ensemble Kalman filter for atmospheric data assimilation. *Mon. Wea. Rev.*, 144, 21-43.

Kalnay, E. and Yang, S.-C., 2010: Accelerating the spin-up of ensemble Kalman filtering. *Q. J. R. Meteorol. Soc.*, 136: 1644-1651.

Keppenne, C.L. et al., 2005: Ensemble Kalman filter assimilation of temperature and altimeter data with bias correction and application to seasonal prediction, *Nonlinear Process. Geophys.*, 12 (4), 491-503.

Krishnamurthy, V. and Shukla, J., 2007: Intraseasonal and Seasonally Persisting Patterns of Indian Monsoon Rainfall. *J. Clim.*, 20, 3-20.

Krishnamurthy, V., 2019: Predictability of Weather and Climate. *Earth Space Sci.*, *6*(7), 1043-1056.

Krishnamurthy, V., and A.S. Sharma, 2017: Predictability at intraseasonal time scale. *Geophys. Res. Lett.*, *44*(16), 8530-8537.

Lea. D.J., J.-P. Drecourt, K. Haines, and M.J. Martin, 2008: Ocean altimeter assimilation with observational- and model-bias correction. *Q. J. R. Meteorol. Soc.*, 134: 1761-774.

Mandke, S.K., Pillai, P.A. and Sahai, A.K., 2020: Simulation of monsoon intraseasonal oscillations in Geophysical Fluid Dynamics Laboratory models from Atmospheric Model Intercomparison Project integrations of Coupled Model Intercomparison Project phase 5. *Int. J. Climatol*., https://doi.org/10.1002/joc.6536.

Martin, M.J. et al., 2015: Status and future of data assimilation in operational oceanography, *J. Oper. Oceanogr.*, 8(S1), s28-s48.

Maturi, E. et al., 2017: A New High-Resolution Sea Surface Temperature Blended Analysis. *Bull. Am. Meteorol. Soc.*, 98, 1015-1026.

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Am. Meteorol. Soc.*, 100, 2509-2532.

Sandery, P.A. et al., 2020: Climate model state estimation using variants of EnKF coupled data assimilation. *Mon. Wea. Rev.*, 148, 2411-2431.

Singleton, T., 2011: Data Assimilation Experiments with a Simple Coupled Ocean-Atmosphere Model, Ph.D. thesis, Dept. of Atmospheric and Oceanic Science, Univ. of Maryland, College Park, Maryland, USA.

Sluka, T.C. et al., 2016: Assimilating atmospheric observations into the ocean using strongly coupled ensemble data assimilation, *Geophys. Res. Lett.*, 43, 752-759, https://doi.org/10.1002/2015GL067238.

Evaluation of High Resolution IMDAA Regional Reanalysis Precipitation over India during Summer Monsoon Season

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1. Introduction

Low resolution datasets generally used to study the variability of the Indian summer monsoon (e.g., Rajeevan et al., 2010; Karmakar, Chakraborty and Nanjundiah, 2017) are not adequate for understanding the local and regional scale monsoon features. Regional reanalysis of high resolution is a plausible solution (Evans and McCabe, 2013). Indian Monsoon Data Assimilation and Analysis (IMDAA) reanalysis is the first successful high-resolution (~12 km), long-period (1979-2018), satellite-era retrospective analysis over India and the surrounding oceanic region. IMDAA reanalysis is a collaborative project among National Centre for Medium Range Weather Forecasting (NCMRWF), India Meteorological Department (IMD) and the UK Met Office under the Monsoon Mission (MM) Programme of the Ministry of Earth Sciences (MoES), Government of India.

One of the fundamental objectives for any reanalysis is to produce time series of meteorological fields that can be used for analyzing the spatio-temporal variability of the climate system. This article evaluates the accuracy and usefulness of IMDAA reanalysis (hereafter IMDAA) rainfall in studying its distribution and variability over India during the summer monsoon season.

2. IMDAA Reanalysis System

IMDAA is a state-of-the-art, satellite-era, high-resolution, and long-term regional reanalysis over the Indian monsoon region. The NWP model used in the IMDAA reanalysis system is the Unified Model (UM) of the UK Met Office (Brown et al., 2012 and the references therein). UM version 10.2 used in IMDAA is configured with 63 vertical levels extending from the surface to a height of ~ 40 km above sea level. The horizontal domain of IMDAA spans from 30°E to 120°E and 15°S to 45°N with a grid spacing of 0.12°× 0.12° having 800 × 576 points in the horizontal. This 12 km resolution reanalysis for the period of 1st January 1979 to 31st December 2018 is currently the highest horizontal resolution reanalysis with the longest period of availability over this region.

The data assimilation method used in IMDAA reanalysis is an incremental four-dimensional variational (4D-Var) method following Rawlins et al. (2007). IMDAA reanalysis has used various conventional and satellite observations from ECMWF, IMD and NCMRWF archives. Variational bias correction method (VarBC) is applied to the satellite radiances (Cameron and Bell, 2018). Soil moisture analysis in the IMDAA system is produced using an Extended Kalman Filter (EKF) based land data assimilation system (deRosnay et al., 2013). High-frequency IMDAA datasets (hourly and three hourly products of various surface and atmospheric fields) are freely available to researchers from https://rds.ncmrwf.gov.in. More details of the IMDAA reanalysis system and its performance are available in Rani et al., (2020), Ashrit et al., (2020) and Mahmood et al., (2018).

3. Results and discussion

3.1 Temporal variability of the Indian summer monsoon rainfall

Fig. 1 shows the monthly accumulated precipitation averaged over the Indian land mass during the summer monsoon months of June, July, August and September from 1979 to 2018 from IMDAA and IMD gridded observation (Pai et al., 2014). The pattern of the all India mean summer monsoon rainfall variability is clearly captured in the IMDAA reanalysis; however, IMDAA is wetter than the observation. IMDAA has captured the excess and deficit rainfall years fairly well. During the normal monsoon years also, the seasonal rainfall from IMDAA is close to the observations as seen in Fig. 1. Another important feature of Fig. 1 is the close agreement between IMDAA rainfall and the observation in the pre-2000 years, but the agreement has been reduced in the post-2000 period. It is worth noting that the gridded observation cannot always be considered as the absolute truth.

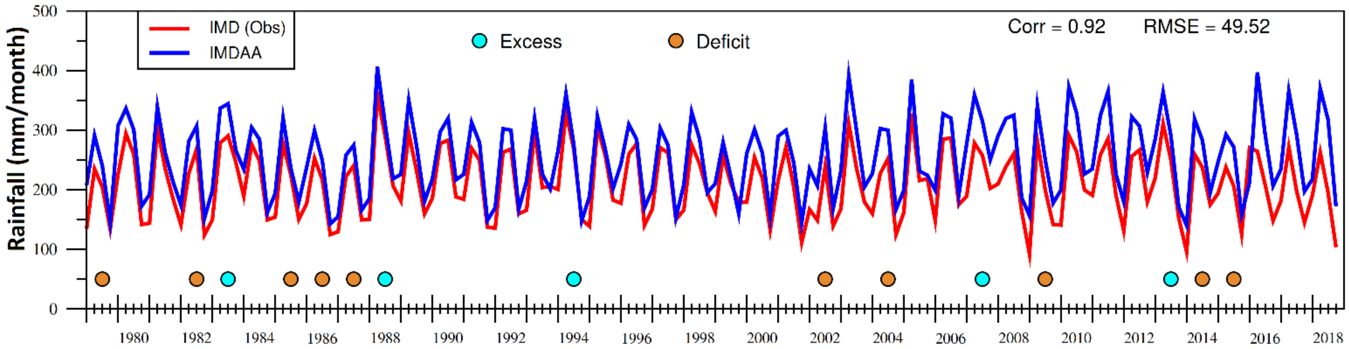

Fig. 1: Time series of monthly accumulated area averaged rainfall over Indian land mass during Indian summer monsoon season (1979-2018) from IMDAA and IMD datasets. Excess and Deficit monsoon years are indicated with aqua and brown circles.

Table 1: RMSE (mm) and correlation coefficient (CC) of IMDAA monthly accumulated rainfall during summer monsoon season (June-September) during the period (1979-2018).

Decades	June		July		August		September	
	RMSE	CC	RMSE	CC	RMSE	CC	RMSE	CC
1979-1988	52.101	0.94	45.626	0.97	34.653	0.94	21.966	0.98
1989-1998	47.150	0.91	39.144	0.78	27.545	0.83	16.467	0.86
1999-2008	67.642	0.94	60.973	0.91	47.726	0.89	28.973	0.84
2008-2018	52.694	0.76	81.218	0.57	73.201	0.67	42.818	0.83

Table 1 shows the Root Mean Square Error (RMSE) in mm and correlation coefficient of the monthly accumulated precipitation averaged over the Indian land mass during each summer monsoon month from IMDAA computed against IMD gridded observations for four different decades. It can be seen from Table 1 that the RMSE is less during the second decade for all the four months and higher during the last decade, except for June, compared to the previous three decades. Both satellite winds and automatic aircraft reports are introduced in the IMDAA system during the second decade. Till 2004, either TOVS (TIROS (Television Infra-Red Observation Satellite) Operational Vertical Sounder) or ATOVS (Advanced TOVS) were the satellite brightness temperatures assimilated, but since 2004, brightness temperatures from other polar and geostationary satellites were introduced. Later on, in the last decade, IMDAA reanalysis system assimilated quite a large number of humidity information from ATMS (Advanced Technology Microwave Sounder), AMSR (Advanced Microwave Scanning Radiometer), and SAPHIR (Sounder for Probing Vertical Profiles of Humidity). RMSEs shows a decreasing trend from June to September, except in the last decade.

The correlation coefficient is found to be high during all four summer monsoon months in the first decade (1979-1988) of the reanalysis with a value above 0.94. Maximum correlation is noticed in June. Correlation of less than 0.8 is observed during the last decade, except for September. The IMDAA precipitation dataset shows consistent and good correlation against observation until the third decade, except for July in the second decade. The correlation coefficient and RMSE of all-India seasonal accumulated mean (40 years) precipitation of IMDAA are 0.92 and 49.5mm respectively.

3.2. Percentage bias and rainfall distribution

Fig. 2a is the spatial plot of IMD observed accumulated precipitation for the summer monsoon period averaged over 40 years (1979-2018). The percentage bias in the seasonal accumulated precipitation over the Indian landmass in the IMDAA with respect to the IMD gridded observation during the same period is shown in Fig. 2b. It is seen that IMDAA is highly wet along the Indo-Gangetic plains and north-east region compared to the IMD gridded observations. Pai et al. (2014) reported that the IMD gridded observations may not represent the actual scenario over the hilly regions, where the number of rain gauge measurements is limited and there are limitations in the interpolation technique used to generate the gridded dataset. IMDAA produced more or less accurate precipitation over the west coast, major parts of peninsular and central India; however, over the east coast IMDAA precipitation is slightly high. Also, it is noted that there is an underestimation of rainfall over the western region and some region of the northern parts of the country in IMDAA. Further analysis of different intensity categories of rainfall shows (figure is not included) that IMDAA has excess light to moderate rainfall compared to the IMD gridded observations.

Fig. 3a and Fig. 3b are the fractional frequency of rainy days (daily accumulated rainfall ≥ 2.5 mm) from observations and IMDAA during the summer monsoon season from 1979 to 2018. IMDAA reproduced the rainy days fairly accurate over

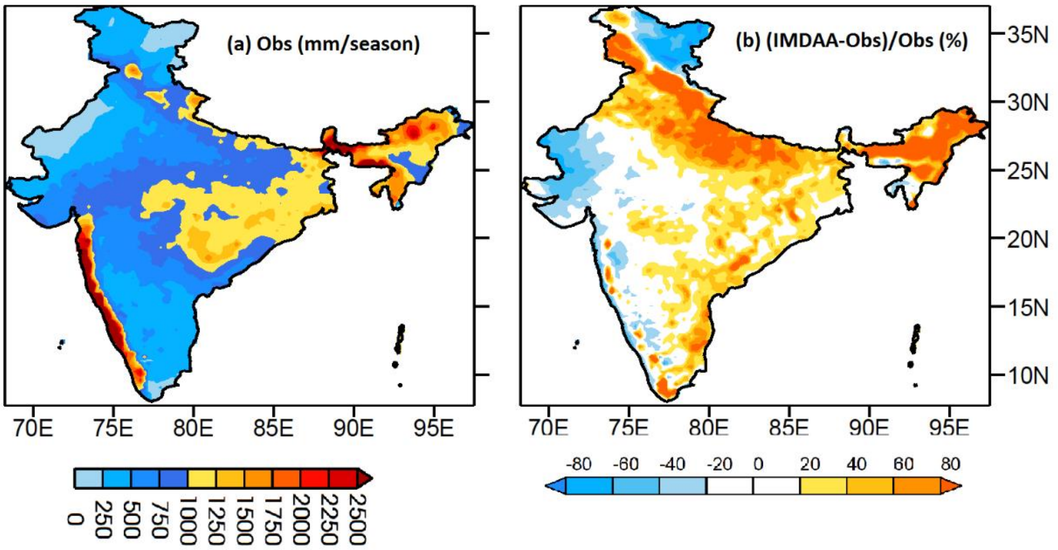

Fig. 2: Observed Indian summer monsoon (June-September) precipitation (mm/season) during 1979-2018 and the corresponding IMDAA bias; (a) Observations, and (b) Percentage bias in IMDAA Reanalysis (Observations are represented by IMD gridded data).

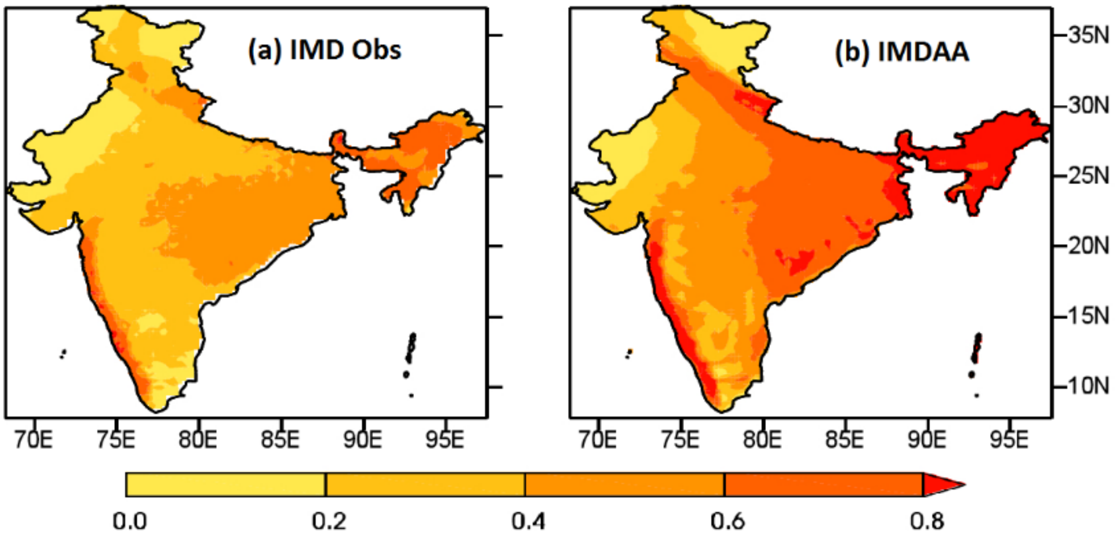

Fig. 3: Relative frequency of rainy days during the Indian summer monsoon season (June-September) during 1979-2018; (a) IMD gridded observations and (b) IMDAA Reanalysis. Both are based on a resolution of 0.25° x 0.25°.

the west coast, peninsular India, western and northern parts of India. However, overly wet days are more frequent in IMDAA over the Indo-Gangetic plains, Himalayan foothills, north-eastern and east-central regions of the country compared to the observations.

4. Summary and Conclusions

Accumulated monthly and seasonal precipitation from the high-resolution IMDAA reanalysis is evaluated against IMD gridded observations for 40 years (1979 to 2018). Temporal variability of all-India monthly accumulated precipitation shows that although IMDAA is wetter compared to the observations, it has captured the monthly variation, seasonal variation and the extreme monsoon years fairly well. It is interesting to note that IMDAA precipitation estimates are impacted by the volume and type of observations assimilated, which invites a detailed investigation. The introduction of automatic aircraft reports and satellite winds during the second decade of the reanalysis reduced the RMSE of IMDAA rainfall. Comparatively poor correlation and RMSE against the IMD gridded observation is noticed during the post-2000 years. Possible discrepancies in the assimilation of large volume of observed humidity information from satellites during the post 2000 years might have played a significant role in this degradation. IMDAA overestimated the light rain categories but failed to produce heavy rainfall as much as in the IMD gridded observations; however, it had more rainy days over a large part of the country, especially over the Indo-Gangetic plains and north-east India, leading to large positive biases in seasonal rainfall over those regions. This study concludes that the high resolution IMDAA reanalysis precipitation dataset can be used for studying spatio-temporal distribution and variability of summer monsoon precipitation over large part of India.

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References

Ashrit, R.G. et al., 2020: IMDAA Regional Reanalysis: Performance Evaluation During Indian Summer Monsoon Season, *J. Geophys. Res.: Atmos.*, https://doi.org/10.1029/2019JD030973.

Brown, A. et al., 2012: Unified modeling and prediction of weather and climate: a 25 year journey, *Bull. Amer. Meteor. Soc.*, 93, 1865-1877, https://doi.org/10.1175/BAMS-D-12-00018.1.

Cameron J., and Bell, W., 2018: The testing and implementation of variational bias correction (VarBC) in the Met Office global NWP system, *Weather Science Technical Report*, No: 631.

de Rosnay, P. et al., 2013: A simplified extended Kalman filter for the global operational soil moisture analysis at ECMWF. *Quart. J. Roy. Meteor. Soc.*, 139(674), 1199-1213, https://doi.org/10.1002/qj.2023.

Evans, J.P., and McCabe, M.F., 2013: Effect of model resolution on a regional climate model simulation over southeast Australia, *Clim. Res.*, 56, 131-145, https://doi.org/10.3354/cr01151.

Karmakar, N., Chakraborty, A. and Nanjundiah, R.S., 2017: Increased sporadic extremes decrease the intraseasonal variability in the Indian summer monsoon rainfall, *Sci. Rep.*, 7:7824, https://doi.org/10.1038/s41598-017-07529-6.

Mahmood, S. et al., 2018: Indian monsoon data assimilation and analysis regional reanalysis: Configuration and performance, *Atmos. Sci. Lett.*, 19, https://doi.org/10.1002/asl.808.

Pai, D.S. et al., 2014: Analysis of the daily rainfall events over India using a new long period (1901-2010) high resolution (0.25° × 0.25°) gridded rainfall data set, *Clim. Dyn.*, 45, 755-776, https://doi.org/10.1007/s00382-014-2307-1.

Rajeevan, M.N. et al., 2010: Active and break spells of the Indian summer monsoon, *J. Earth. Syst. Sci.*, 119(3), 229-247.

Rani, S.I. et al., 2020: IMDAA: High Resolution Satellite-era Reanalysis for the Indian Monsoon Region, *J. Clim.*, (*Under Review*).

Rawlins, F. et al., 2007: The Met Office global 4-dimensional data assimilation system, *Quart. J. Roy. Meteor. Soc.*, 133, 347-362, https://doi.org/10.1002/qj.32.

Improving Monsoon Simulations through Multi-scale Multi-cloud Parameterization

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A major challenge in contemporary parameterizations of cumulus convection is associated with their inability to capture the interactions across multiple temporal and spatial scales of cloud systems in the tropics. This is evident in the poor performance of climate and earth system models in simulating the tropical rainfall variability and the associated multiple synoptic and planetary scale tropical wave modes, such as convectively coupled waves, the Madden Julian Oscillation, and the Indian monsoon intra-seasonal oscillations. Here, we point to the recent improvements in this regard by the simple replacement of the Arakawa-Schubert parameterization for deep convection, in NCEP's Climate Forecasting Model, by a stochastic multi-cloud model (SMCM) parameterization. The SMCM is based on the representation of the multiple cloud types that characterize deep convection by an order parameter that takes discrete values on a square lattice overlaid on top of each model grid box and evolve dynamically as a Markovian process with transition probabilities depending on the large-scale (model resolved) dynamics and thermodynamics.

1. Introduction

The inability of the state-of-the-art cumulus parameterizations to capture the multiscale convective organization in the tropics is due in large part to the underlying closure being based on the quasi-equilibrium assumption (QEA) (Arakawa and Schubert, 1974; Zhang and McFarlane, 1995; Khouider and Leclerc, 2019). Many breakthroughs have been achieved in the last twenty years or so, in overcoming the QEA dilemma (Rio et al., 2019). The proposed alternatives to the QEA include the use of probabilistic models in order to represent the missing sub-grid variability and mimic the stochastic nature of convection (Berner et al., 2017). In particular, Khouider et al. (2010) have proposed a stochastic multi-cloud model (SMCM) that represents the multiple cloud types that characterize organized tropical convection (Johnson et al., 1999) and their interactions across scale with each other and with the large scale (resolved) dynamics. The implementation of several variants of the SMCM in GCMs has led to striking improvements (Dorrestijn et al., 2016; Peters et al., 2017; Goswami et al., 2017a,b,c; Khouider, 2019).

One of the fundamental features of the SMCM is representing the self-similar dynamical structure of the tropical convective systems and the associated cloud life cycle (Mapes et al., 2006; Cardoso-Bihlo et al., 2019). The SMCM features congestus cloud decks that pop out above the trade wind inversion layer, which caps and traps shallow cumulus, and de-train near the freezing level when the environment is dry (Johnson et al., 1999). The congestus clouds are then followed by deep convective cumulonimbus that reach near the tropopause when the atmosphere is moistened and preconditioned due in large part to the shallow and cumulus congestus activity (Khouider and Majda, 2008; Waite and Khouider, 2010; Hohenegger and Stevens, 2013). Stratiform anvils follow in the wake of deep convection and help enforce unsaturated downdrafts associated with the evaporation of stratiform, which stabilize the boundary layer and help restore the trade wind inversion for shallow cumulus convection to thrive once again and the cycle is closed.

Goswami et al. (2017*a*,*b*,*c*) have implemented the SMCM in the second version of the Climate Forecasting System (CFSv2) of the National Centers for Environmental Predictions (NCEP). They showed that when coupled to the SMCM, the CFS model (CFE-SMCM) improves drastically the simulation of, in particular, the main tropical modes of atmospheric variability such as convectively coupled waves, the MJO, and monsoon intra-seasonal oscillations as well as the climatology of the rain events distribution.

2. The SMCM in CFS

To showcase the striking performance of the CFS-SMCM, in comparison with the default CFSv2 model, which uses the relaxed Arakawa-Schubert parameterization, we show here a few of the results reported in Goswami et al. (2017*a*,*c*).

In Fig. 1, we show the low-frequency spectra for both the North-South and the East-West propagating wave signals. From the East-West plots in the bottom panels, we can identify two major deficiencies in the CVFv2 simulation that are greatly corrected in the CFS-SMCM run. First, at wavenumber one, the MJO-signal peaks below 60 days in CFSv2 while it is more around and slightly above 45 days in the observation. In CFS-SMCM, the strongest MJO peak is between 45 and 30 days, which is much closer to the observation although there is still some discrepancy. Second, the CFSv2 power has a relatively stronger peak left of wavenumber zero, corresponding to west-ward propagating Rossby waves, that also seem to be much slower than the observations. The CFS-SMCM, however, showcases an eastward-westward power ratio which is more consistent with the observation. The CFS-SMCM Rossby wave period appears also to be closer to the observed one.

The top panels of Fig. 1 show the spectral power of North-South propagating low-frequency signals over the Indian Monsoon region. The two simulated northward propagating signals are both weaker than their observed counterpart. This is also true for the MJO peaks on the bottom panels. Clearly, there is still room for improvement for both models in this regard. Moreover, the CFSv2 simulation has a northward propagation period which is larger than the one from the observation, which shows a signal that peaks around 45 days and expands vertically to up to 20 days. This extension to higher frequencies is well captured by the CFS-SMCM, although the signal is weaker. The slow northward propagation in the CFSv2 simulation is remarkably consistent with the slower periods of its MJO and Rossby wave disturbances.

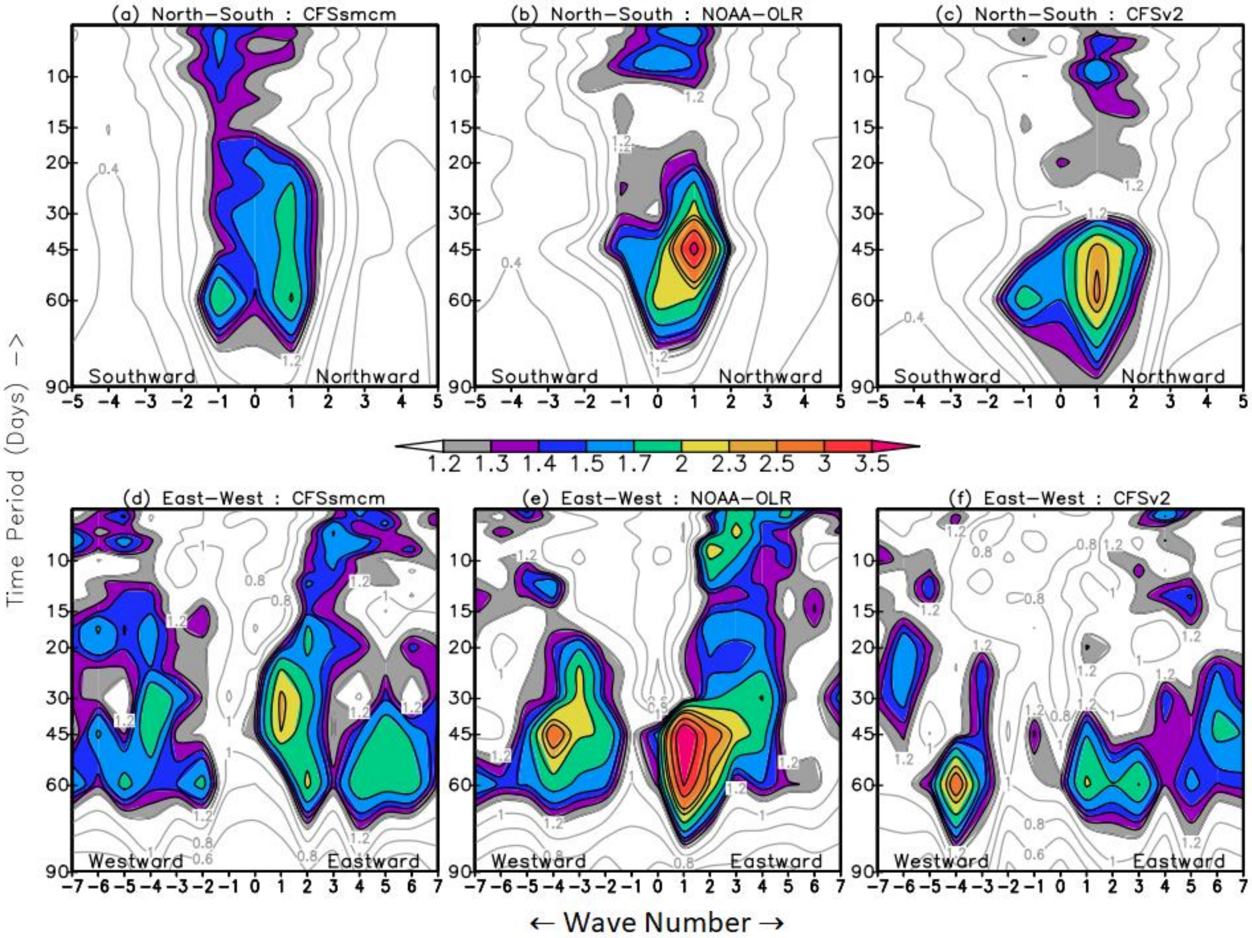

Fig. 1: Low-frequency power spectra for North-South (top) and East-West (bottom) spectral power for CFS-SMCM (left), observations (middle) and CFSv2 (right).

It is one thing for a climate model to simulate a low-frequency oscillation signal. However, the ultimate question is whether this signal bears any resemblance to the targeted observed phenomenon one is aiming for. In Fig. 2, we plot the composited physical structures of OLR and zonal winds of the MJO and MISO signals for the two simulations and the observations (NOAA OLR and NCEP reanalysis winds). It is clear from Fig. 2, that what everybody calls the MJO peak in the spectral diagram of CFSv2 (Fig. 1) bears very little resemblance to the true MJO as observed in nature both in terms of OLR and zonal winds in this case. A more exhaustive comparison has been carried in Goswami et al. (2017*a*) and the same is true for almost all variables including (essentially) moisture, temperature, and vertical velocity. As can be seen in Fig. 2A,B for instance, while in both the observations and the CFS-SMCM simulation, the OLR has a sharp minimum around 90E, the CFSv2 simulation displays a maximum around 120E. The zonal wind composite in the CFS-SMCM simulation and the NCEP data have a slightly tilted (-mainly first) baroclinic structure with converging winds in the lower troposphere and divergent winds in the upper troposphere coinciding with the OLR minimum. The CFSv2 run on the other has a completely unmatched zonal wind composite structure, which is also much weaker. Both the sharp OLR minimum and the associated baroclinic structure are proven to be important for the MJO's wave dynamical morphology and the physical processes behind its coupling with convection Kiladis et al. (2009); Khouider (2019); Majda and Stechmann (2009).

The fact that CFSv2 has an MJO-like frequency signal that doesn't include such features suggests that some climate models may produce MJO signals for non-physical reasons, i.e, that are simple numerical artifacts that have no bearing with the reality.

From Fig. 2A,B, CFSv2 seems to do a better job in terms of the MISO composite structures compared to its MJO performance. However, even in the MISO case, the CFVv2 run has some serious shortcomings that are highly improved in the CFS-SMCM simulation. For instance, the OLR minimum peak is less weak, compared to the observation, in the CFS-SMCM simulation than in the CFSv2 run. The northward winds, sandwiched between the Equator (EQ) and the minimum OLR location (delimiting the low-level convergence), are confined to the lower part of the troposphere, below 500 hPa while in both the observations and the CFS-SMCM run they penetrate much deeper, toward the tropopause.

The joint distributions of rainfall and OLR event frequencies for both the CFS-SMCM and the CFSv2 simulations and the TRMM-NOAA data are shown in Fig. 3 for the ISM region (in time and space) and the annual distributions over the entire tropics, separately. It is a known fact that rainfall events of 200 mm per day and higher are produced by deep and high clouds, which are characterized by low OLR values while thin cirrus and shallow cumulus and cumulus congestus clouds typically drizzle or produce only light rain events. This is consistent with the plots in Figs. 3 (a) and (d). We can see also

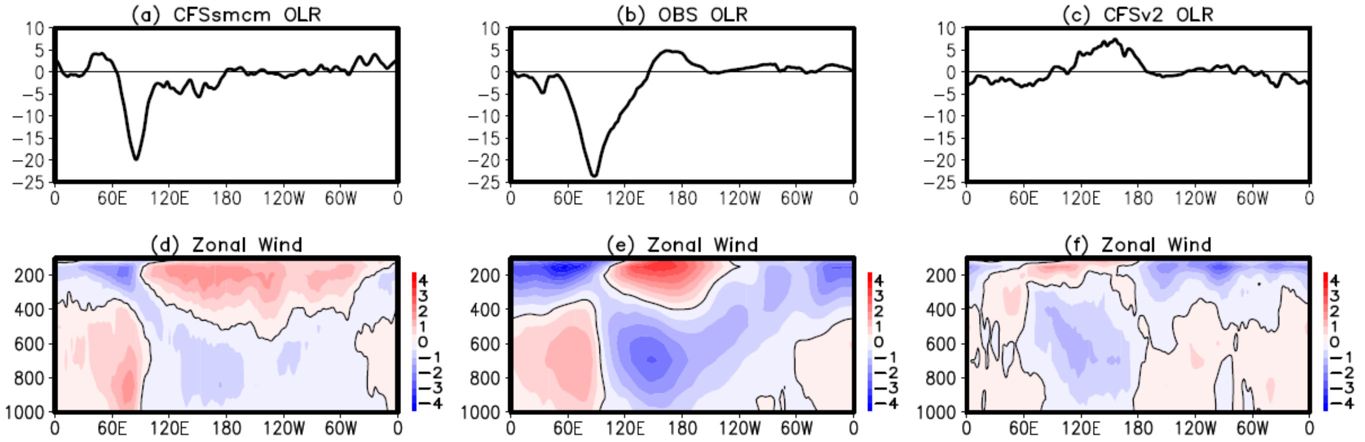

Fig. 2A: Longitude-height cross section (averaged for 5°S-5°N) of MJO composite of the MJO-filtered (a)-(c) OLR (Wm^{-2}) anomalies and the corresponding anomalous (d)-(f) zonal wind (ms^{-1}); (a) and (d): CFS-SMCM; (b) and (e): Observations; (c) and (f): CFSv2.

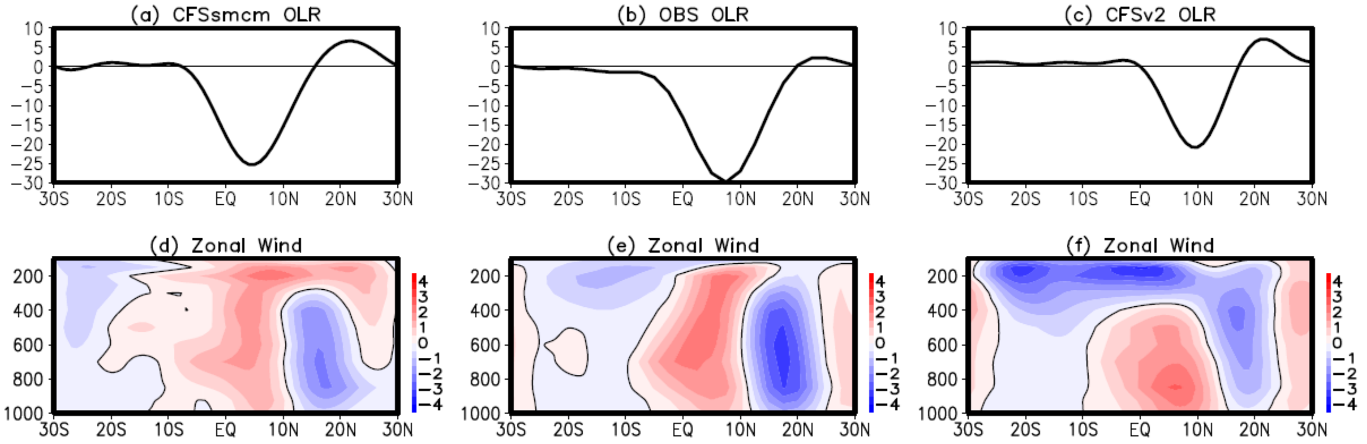

Fig. 2B: Latiitude-height cross section (averaged for 70°-90°E) of MISO composite of the MISO-filtered (a)-(c) OLR (Wm^{-2}) anomalies and the corresponding anomalous (d)-(f) zonal wind (ms^{-1}); (a) and (d): CFS-SMCM; (b) and (e): Observations; (c) and (f): CFSv2.

that while strong rainfall events are typically more concentrated in the OLR-rainfall plane, they also exhibit a fair amount of scattering along the OLR axis. State-of-the-art GCMs using deterministic parameterizations tend to produce too much light rainfall events as the underlying cumulus parameterizations tend to produce rain and form deep clouds too often and too quickly. This is the case for the CFSv2 simulation results in Figs. 3 (b) and (e). The CFS-SMCM on the other hand produces rainfall-OLR distributions that are more in line with the observations, both in terms of low OLR associated with high rainfall events and of the significant scattering of the event frequencies (Figs. 3 (c) and (f)). This is thanks to the multi-cloud paradigm of inhibiting deep convection when the atmosphere is dry to allow the buildup of convective available potential energy (CAPE) and moisture and prevent the drizzling to occur during deep convection, and also to systematically build in a stochastic representation of the organized convection statistics and the inherent interactions across multiple scales.

3. Conclusion

The multi-cloud model (MCM) paradigm offers an appealing point of view for modelling and understanding tropical convective systems at multiple scales. It is the building block for the representation and parameterization of organized convective systems that present a great deal of self-similarity (Khouider and Majda, 2006; Mapes et al., 2006; Majda, 2007). As such it has been very successful in explaining the propagation and the dynamical features of convectively coupled waves and the role played by multiple cloud types in coupling these waves and convection across a wide range of temporal and spatial scales (Khouider, 2019; Moncrieff, 2019).

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References

Arakawa, A. and Schubert, W.H., 1974: Interaction of a cumulus cloud ensemble with large-scale environment, part I, *J. Atmos. Sci.* 31(3), 674-701.

Berner, J. et al., 2017: Stochastic parameterization: Towards a new view of weather and climate models, *Bull. Am. Meteorol. Soc.,* 98(3), 565-588.

Cardoso-Bihlo, E. et al., 2019: Using radar data to calibrate a stochastic parametrization of organized convection, *J. Adv. Modeling Earth Sys.* 11, 1655-1684.

Dorrestijn, J. et al., 2016: Stochastic convection parameterization with Markov chains in an intermediate-complexity GCM, *J. Atmos. Sci.,* 73(3), 1367-1382.

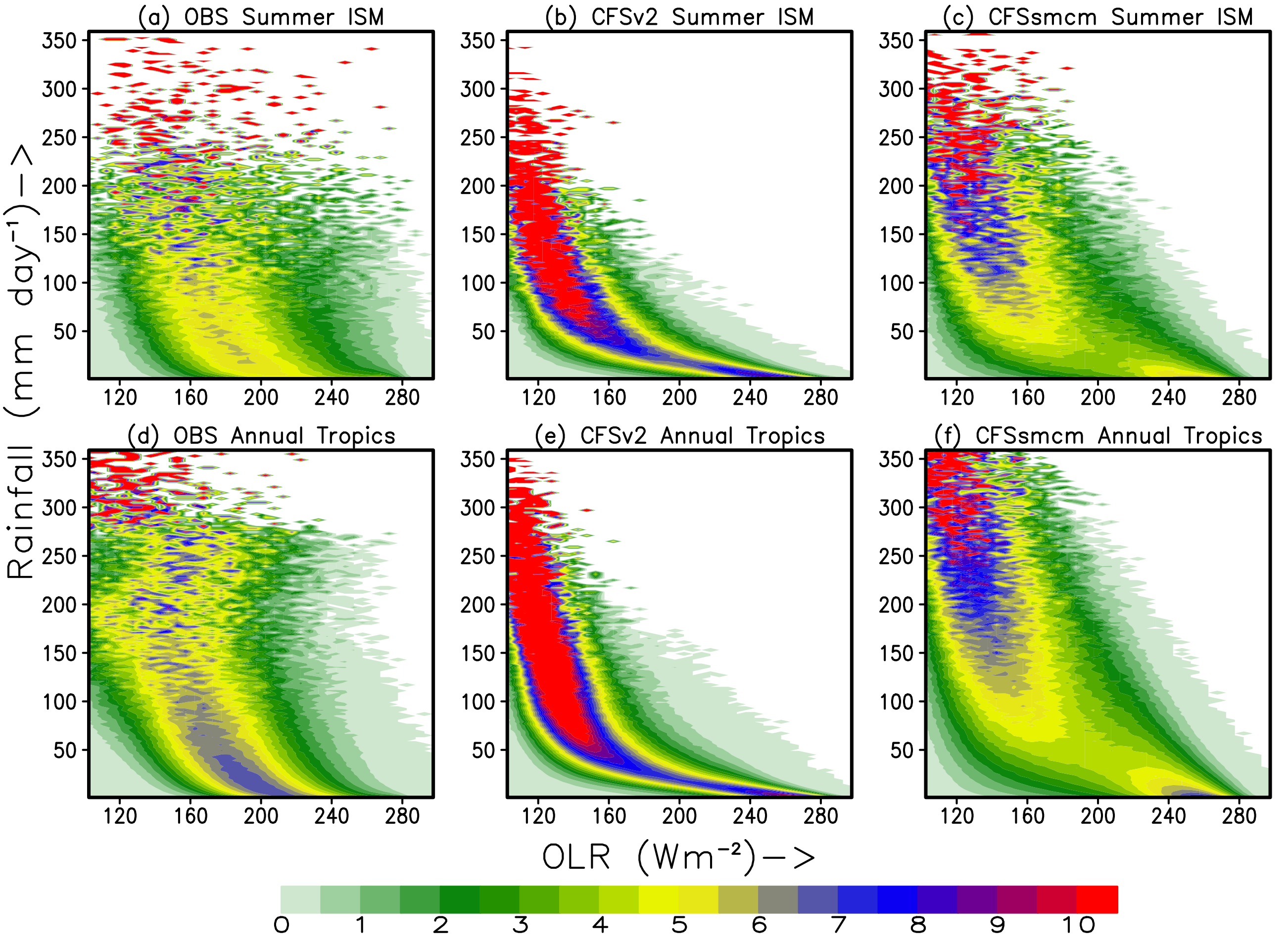

Fig. 3: Frequency distributions of rainfall and OLR events averaged over the Indian monsoon region (15S- 30N, 50E-110E) during the summer-JJA (a,b,c) and over the tropical belt (30S-30N) for all seasons (d,e,f). (a) and (d): Observation (TRMM-NOAA); (b) and (e): CFSv2; (c) and (f): CFS-SMCM.

Goswami, B.B. et al., 2017*a*: Implementation and calibration of a stochastic convective parameterization in the NCEP Climate Forecast System, *J. Adv. Model. Earth Syst.,* 9, 1721-1739.

Goswami, B.B. et al., 2017*b*: Improved tropical modes of variability in the NCEP Climate Forecast System (version 2) via a stochastic multi-cloud model, *J. Atmos. Sci.,* 74, 3339-3366.

Goswami, B.B. et al., 2017*c*: Improving synoptic and intra-seasonal variability in CFSv2 via stochastic representation of organized convection, *Geophys. Res. Lett.* 44, 1104-1113.

Hohenegger, C. and Stevens, B., 2013: Preconditioning deep convection with cumulus congestus, *J. Atmos. Sci.* 70(2), 448-464.

Johnson, R. H. et al., 1999: Tri-modal characteristics of tropical convection', *J. Clim.,* 12(8), 2397-2418.

Khouider, B., 2019: *Models for Tropical Climate Dynamics: Waves, Clouds, and Precipitation*, Mathematics of Planet Earth series, Volume 3, Springer, 303 pp., https://doi.org/10.1007/978-3-030-17775-1.

Khouider, B., Biello, J. and Majda, A.J., 2010: A stochastic multicloud model for tropical convection, *Commun. Math. Sci.* 8(1), 187-216.

Khouider, B. and Leclerc, E., 2019: Toward a stochastic relaxation for the qe theory of cumulus parameterization, *J. Adv. Model. Earth Syst.,* 11(8), 2474-2502, https://doi.org/10.1029/2019MS001627.

Khouider, B. and Majda, A.J., 2006: A simple multi-cloud parameterization for convectively coupled tropical waves. Part I: Linear analysis', *J. Atmos. Sci.* 63, 1308-1323.

Khouider, B. and Majda, A.J., 2008: Multicloud model for organized tropical convection: Enhanced congestus heating', *J. Atmos. Sci.* 65, 895-914.

Kiladis, G.N. et al., 2009: Convectively coupled equatorial waves', *Rev. Geophys.* 47, RG2003, https://doi.org/10.1029/2008RG000266.

Majda, A.J., 2007: Multiscale models with moisture and systematic strategies for super-parameterization, *J. Atmos. Sci.* 64, 2726-2734.

Majda, A.J. and Stechmann, S.N., 2009: The skeleton of tropical intra-seasonal oscillations, *Proc. Natl. Acad. Sci. USA,* 106, 8417-8422.

Mapes, B. et al., 2006: The mesoscale convection life cycle: Building block or prototype for large-scale tropical waves?, *Dyn. Atmospheres Oceans,* 42(1-4), 3-29.

Moncrieff, M.W., 2019: Toward a dynamical foundation for organized convection parameterization in GCMs', *Geophys. Res. Lett.,* 46(23), 14103-14108.

Peters, K. et al., 2017: Improved MJO-simulation in ECHAM6.3 by coupling a stochastic multicloud model to the convection scheme, *J. Adv. Model. Earth Syst., 9(1), 193-219,* https://doi.org/10.1002/2016MS000809.

Rio, C., Del Genio, A. and Hourdin, F., 2019: Ongoing breakthroughs in convective parameterization, *Curr. Clim. Change Rep.,* 5, 95-111, https://doi.org/10.1007/s40641-019-00127-w.

Waite, M. and Khouider, B., 2010: The deepening of tropical convection by congestus preconditioning, *J. Atmos. Sci.,* 67, 2601-2615.

Zhang, G.J. and McFarlane, N.A., 1995: Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Center general circulation model, *Atmos.-Ocean,* 33(3), 407-446, https://doi.org/10.1080/07055900.1995.9649539.

Indo-UK Joint Monsoon Campaign: Projects under Monsoon Mission

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1. Motivation and funding context

The South Asian summer monsoon provides around 80% of annual rainfall to more than a billion people reliant on its rains, in particular for agriculture. Accurate prediction of the timing, intensity and duration of monsoon rainfall is therefore a strong societal need, on time scales from daily weather forecasting up to multi-decadal changes in climate. Despite this need, models used in monsoon prediction suffer large systematic biases in several processes in the atmosphere, ocean and on the land surface.

Following a successful working relationship between the UK's Natural Environment Research Council (NERC) and India's Ministry of Earth Sciences (MoES) established during the Changing Water Cycle programme, MoES/NERC identified an opportunity to improve land-atmosphere-ocean science related to the monsoon through better measurement and understanding of processes at small space and time scales. These include land-ocean-atmosphere interactions (vital for understanding monsoon intraseasonal variability which controls the timing of the rains on time scaled of a few weeks) and aerosol processes relating to the large local emissions of sulphates, black carbon and dust (which have important radiative and cloud microphysical effects with feedbacks on climate as well as significant consequences for air quality and human health). Due to the scale of these interactions, they are often parameterized in models and the source of several biases.

The joint funding framework for the three field campaigns to be outlined here arose from NERC's Drivers of variability in the South Asian Monsoon programme and the MoES Monsoon Mission to improve prediction of the monsoon from short-range to seasonal time scales. As described in Rao et al. (2019), the Monsoon Mission is an activity targeted at improvements to dynamical prediction in a pair of models: The Climate Forecast System, version 2 (CFSv2), and the Met Office Unified Model (MetUM).

The work of the Indo-UK programme had a remit of understanding the links between small-scale processes and larger scale monsoon variability by combining analysis of new and historical observations, as well as from high resolution modelling and data assimilation. A unique feature of the programme was the provision of twin observing platforms during the June-July period of the monsoon in 2016. These are the UK Facility for Airborne Atmospheric Measurements (FAAM) research aircraft, a converted Bae-146 jet (which undertook the first mission of a foreign research aircraft to India during this programme), and the ocean Research Vessel (RV) Sindhu Sadhana. Additional support came from the Met Office in provision of aircraft mission scientists and dedicated instrument operators as well as bespoke weather forecasting.

The three field campaigns, discussed below in more detail, are:

- Interaction of Convective Organization and Monsoon Precipitation: Atmosphere Surface and Sea (INCOMPASS): led by G.S. Bhat (Indian Institute of Science) and A.G. Turner (University of Reading);
- South West Asian Aerosol Monsoon Interactions (SWAAMI): led by S. Suresh Babu (Indian Space Research Organization) and H. Coe (University of Manchester);
- Bay of Bengal Boundary Layer Experiment (BoBBLE): led by P.N. Vinayachandran (Indian Institute of Science) and A.J. Matthews (University of East Anglia).

The INCOMPASS and SWAAMI campaigns shared use of the FAAM aircraft in 22 flights, while BoBBLE used RV Sindhu Sadhana as its observational base. Administrative support was provided by the Indian Institute of Tropical Meteorology, Pune.

Emerging results from the three field campaigns are described below.

2. INCOMPASS

As described in Turner et al. (2020), the INCOMPASS field campaign was designed to better understand how an air parcel is modified as it travels towards India, crossing the coast of the Arabian Sea, the Western Ghats mountains and over a variety of land surface types and soil moisture patterns. Further study is focused on the transitions between marine and continental air for flows passing from the Bay of Bengal. INCOMPASS launched its research flights from two locations over June-July 2016: (i) Lucknow, in northern India, provides a means of examining how the overlying atmosphere responds to soil moisture in the Indo-Gangetic Plains (IGP), arising either from irrigation or from antecedent rainfall, in addition to the coastal transition; (ii) Bengaluru in southern India, from where flights were able to sample the impact on convection of the coastal transition from the Arabian Sea and over the Western Ghats orography. In addition, flights were taken across the rain shadow of southeast India and across the coast into the southwest Bay of Bengal. These flights included an overpass of the RV Sindhu Sadhana operated by BoBBLE. Flight planning for the INCOMPASS and SWAAMI field campaigns greatly benefited from a mock forecasting exercise held during the monsoon a year earlier (Willetts et al., 2017) and the comprehensive range of modelling and forecast tools offered by the Met Office in conjunction with India's NCMRWF (Martin et al., 2020). Convective scale NWP models run at NCMRWF have also been assessed in comparison to flight data (Jayakumar et al., 2020).

Work in observations and reanalysis motivated by INCOMPASS has already suggested a new paradigm for the monsoon onset (Parker et al., 2016), suggesting it to be a tug-of-war between advancing tropical flow at low levels in southern India and a retreating dry intrusion emanating from the north west. As the monsoon progresses, the dry intrusion is eroded from below and from the south east, aided by the detrainment of moisture by shallow convection at the freezing level (and confirmed in the modelling studies of Menon et al., 2019). More detailed case studies of the 2016 season using convection-resolving models (Volonté et al., 2020) have further highlighted the role of the extratropics in partially controlling the rate at which the monsoon progresses across India. Rather than a smooth retreat, the dry-air intrusion is shown to jerk back and forth, hypothesized to relate to Rossby wave perturbations on the subtropical jet.

While other monsoon processes such as ocean-atmosphere interaction have been heavily studied (including during the BoBBLE campaign, see later), the role of the land surface has often been overlooked. In particular, how the land surface feeds back on the progression of the monsoon through its seasonal cycle, or during monsoon intraseasonal variability, is ripe for study due to the paucity of observations related to the role of the land surface in driving convection over India. To start alleviating this, INCOMPASS installed a series of eddy-covariance flux towers across the country on a variety of surface types. Early results of the diurnal cycle of surface fluxes from these towers are described in Bhat et al. (2020), including the clear transition in the partitioning between dominance by sensible and latent heat fluxes as the monsoon onset passes, and the demonstration of the likely underestimation of latent heat in models. An example of this was provided by Chakraborty et al. (2019) who used data from one of the flux-tower sites, Kanpur, in northern India. Comparison with the Noah land-surface model over the 2016 and 2017 seasons revealed the model to overestimate sensible heat fluxes around the middle of the day, at the expense of latent heating. These biases were found to be even worse in coupled model simulations. By modifying Noah simulations with vegetation parameters relevant to the site, Chakraborty et al. (2019) demonstrated an improved partitioning of the turbulent heat fluxes and reduced biases in soil and skin temperature as simulated by the model. Further land surface observation can thus inform the parameters used in model simulations and reduce biases.

By combining flux tower outputs with other meteorological observations, upper-air profiles and transects of the overlying atmosphere from the flight missions, INCOMPASS aimed to interrogate the land-atmosphere interactions during monsoon variability. The importance of mesoscale soil moisture gradients over northern India in initiating convection has been demonstrated by Barton et al. (2020), using a case study to show that local convergence patterns are generated in the boundary layer over transitions between wet and dry soils. These lead to shallow convection, which satellite retrievals show to deepen later during the diurnal cycle, leading to storms. The extent to which this happens during the monsoon and across India needs to be better established and evaluated in models.

Finally, based on the comprehensive set of flight and flux-tower data from the southern portion of the campaign in Bangalore, Fletcher et al. (2020) demonstrated case studies of distinct regimes of offshore and onshore convection in the vicinity of the Western Ghats mountains. The transition to onshore rainfall was accompanied by a dry intrusion over the Arabian Sea, suppressing mid-tropospheric moisture and limiting convection there. Work subsequent to INCOMPASS (Hunt et al., 2020) has revealed these offshore-onshore transitions to be a more general feature of the monsoon, with some degree of large-scale control exerted by the boreal summer intraseasonal oscillation. This reveals the possibility of improved predictions in the region.

3. SWAAMI

To fill key gaps in our knowledge of aerosol properties and their impacts on cloud and radiation, a pair of studies (Brooks et al., 2019a, 2019b) used FAAM flight observations from the northern India Lucknow base separated into (local) pre-monsoon and monsoon cases, over 11-12 June and 30 June-11 July 2016 respectively. In addition to standard meteorological instruments, the FAAM aircraft is equipped for assessing atmospheric composition and chemistry, including an aerosol mass spectrometer to separate aerosol species, and a single-particle soot photometer (SP2) for measurements of refractory black carbon. Aerosol number concentrations could be provided by a passive cavity aerosol spectrometer probe and cloud droplet probe.

The IGP is known to feature high aerosol mass concentrations prior to the monsoon. Brooks et al. (2019a) performed a physical and chemical characterization of submicron aerosol, the first to obtain airborne in situ measurements across northern India. Below 1.5 km, organic and absorbing aerosol were found to dominate, while above this there was strong evidence of dust transport from the Thar Desert in northwest India, in addition to sulphates and other species. Arrival of the monsoon squashed the aerosol layer to a maximum height of around 2 km.

Meanwhile, Brooks et al. (2019b) used FAAM's on board SP2 to measure the mixing state of particles containing black carbon. The arrival of monsoon rains led to decreased mass concentrations of black carbon in the central and eastern IGP. Following the onset, the coating thickness and mass absorption cross section were maintained over the central IGP but reduced over the north east and north west of the region. The study also determined the dominant emissions source at play across the IGP. Wood-burning emissions formed the dominant contribution to black carbon aerosol, with particles of moderate coating. But as the monsoon advances into the northeast, smaller uncoated particles were detected. Traffic emissions were found to be the dominant source of black carbon in the northwest in both pre-monsoon and monsoon periods. The findings of Brooks et al. (2019b) may have important implications for the constraint of radiative forcing in aerosol models and for black carbon emission inventories.

Further works such as Kompalli et al. (2020) have used refractory black carbon measurements over Bhubaneswar, near to India's east coast, derived from an SP2 also installed on the ground as part of the SWAAMI campaign. Its measurements during July 2016-May 2017 have allowed a microphysical characterization of different airmasses, including the outflow from the IGP, with implications for their effect on climate.

Finally, SWAAMI also offered the first estimates of the vertical structure of single scattering albedo (SSA) and its spatial variation over northern India and the Bay of Bengal via in situ measurements from the aircraft. Prior to the monsoon onset, Manoj et al. (2020) found strong aerosol absorption over the Indo-Gangetic plains, with a gradient to lower values in the arid north-west of the country. While much less absorption was measured as the monsoon transitioned to active conditions, there was still persistent absorption in the low and middle troposphere. By using a radiative transfer model, Manoj et al. (2020) compared the effects of vertically resolved inputs of SSA with traditional single-column values, finding that the single-column approach would underestimate heating rates in regions with strongly absorbing aerosols. The more realistic profiles also demonstrated strong heating of the mid-troposphere, which is suggested to have implications for the effects of cloud on climate.

Outcomes from the SWAAMI aircraft campaign are already being used to inform the study of air quality in the Delhi region. Black carbon particle measurements from SWAAMI (Brooks et al., 2019b) have been used to improve the configuration of pollution dispersion models for simulating the effects of crop-burning practices during autumn (Takigawa et al., 2020).

4. BoBBLE

The BoBBLE field campaign, summarized in Vinayachandran et al. (2018), was strongly motivated by the potential role played by the Bay of Bengal in controlling Indian monsoon variability, particularly at intraseasonal time scales. Compared to its surroundings, the southwest Bay of Bengal is cooler and more saline and falls under the rain shadow region of southeast India during the summer monsoon months. Despite these unusual features, it remains under sampled. Instruments on the RV Sindhu Sadhana expedition during June-July 2016 comprise a conductivity-temperature-depth (CTD) profiler, a vertical microstructure profiler, two acoustic Doppler current profilers, and a meteorological tower including flux sensors. From the vessel, radiosonde launches provided upper-air measurements while five semi-autonomous underwater sea gliders explored programmed 3D routes. These observations were combined with others from Argo floats, drifting buoys and satellite remote sensing. The campaign focused on a zonal section at 8°N between 85.3° and 89°E.

As reported in Vinayachandran et al. (2018), BoBBLE's key results include aspects of the seasonal evolution of the Sri Lanka Dome and Southwest Monsoon Current, including the passage of two freshening events in the upper layer of ocean, forming thick barrier layers. During a break phase in the monsoon, BoBBLE measurements have shown warming of the mixed layer and its impact on pre-conditioning the overlying atmosphere to convection.

Motivated by the lack of understanding of the drivers for SST variability in the Bay of Bengal and their importance to the monsoon and other phenomena such as tropical cyclones, Vijith et al. (2020) used the comprehensive in situ observations from BoBBLE to perform the first full closure of the mixed-layer energy budget in the region. The chief finding was that horizontal advection and entrainment contribute more than expected to SST evolution. Given the poor resolution of these processes in climate models, further efforts are needed to quantify the mixed layer energy budget in a more comprehensive manner, and in comparison, with that in models, in order to improve process understanding of this important driver of monsoon rainfall variability.

George et al. (2019) used a vertical microstructure profile to generate a 10-day time series in the southern Bay of Bengal at 8°N, 89°E from 4 to 14 July 2016. The time series was enough to capture periods of barrier layer erosion and reformation and revealed a complex structure comprising a fresh surface mixed layer, a barrier layer, below which there was a high salinity core layer. The relative horizontal motion between the layers leads to high shear. Under conditions of barrier layer erosion, the three-layer structure was replaced with a deep mixed layer, weakening the stratification and allowing wind forcing to penetrate deep into the ocean. These observations combined with 1D-model experiments confirmed the close link between ocean dynamics and air-sea interaction processes.

Further measurements provided by BoBBLE enabled the sampling of the chlorophyll distribution in the south Bay of Bengal using sea gliders and CTD profiles launched from the ship. As reported in Thushara et al. (2019), observations were made for up to 20 days, focused on the Sri Lanka Dome and Southwest Monsoon Current regions. The findings emphasize the need for better in situ sampling and ocean biophysical modelling in order to quantify any potential climate feedbacks from chlorophyll. Meanwhile, Sheehan et al. (2020) used a combination of BoBBLE sea glider observations, ocean reanalysis and trajectory experiments to show the existence of water emanating from the Persian Gulf in the southwest Bay of Bengal, transported by currents taking between two and three years. Through the annual cycle, the strongest influx of this water mass is found to occur during the summer monsoon. Sheehan et al. (2020) hypothesize that the injection of this water into the Bay's oxygen minimum zone serves to keep oxygen levels above the denitrification threshold.

Finally, analysis arising from BoBBLE has assessed common reanalysis products against in situ ocean observations from the RAMA array (Sanchez-Franks et al., 2018). Of the comparisons made, TropFlux and ERA-Interim were found to provide the best representation of monsoon intraseasonal variability for surface fluxes and associated meteorology.

5. Outlook

The Indo-UK joint monsoon campaigns generated renewed enthusiasm for existing collaborations and gave impetus for substantial new collaborations between scientists in the UK and India. The field campaigns also gave experience to large numbers of early career scientists from both countries, in daily forecast briefings, scientific flight planning, flight mission work and instrument deployment.

Given the findings on land-atmosphere interaction, ocean-atmosphere interaction and aerosol composition, renewed efforts are required to gather further observations in the India region to demonstrate the robustness of the findings and test hypotheses. This should include further field campaigns and the establishment of new long-term measurements in order to define mechanisms. For example, it is recognised by Lewis et al. (2019) in the development of a Met Office coupled convective-scale modelling strategy for India that a much greater range of air-sea flux observations are required in order to improve process understanding and enable better model evaluation. Likewise, the INCOMPASS results on the importance of land surface forcing need to be tested more comprehensively across India and land-atmosphere interactions examined more carefully using continued flux tower measurements, point-scale modelling of the land surface and comparison to GCMs.

The overriding motivation of the Monsoon Mission is to improve the prediction systems used for the monsoon, particularly at the short range, extended range and seasonal time scales. This needs the strong support of parametrization development in response to new observations such as those from INCOMPASS, SWAAMI and BoBBLE.

Flight data are freely available upon registration at http://data.ceda.ac.uk/badc/sa-monsoon.

References

Barton, E.J., et al., 2020: A case-study of land-atmosphere coupling during monsoon onset in northern India. *Q. J. R. Meteorol. Soc.*, 146: 2891-2905. https://doi.org/10.1002/qj.3538.

Bhat, G.S. et al., 2020: Spatial and temporal variability in energy and water vapour fluxes observed at seven sites on the Indian subcontinent during 2017. *Q. J. R. Meteorol. Soc.*, 146: 2853-2866. https://doi.org/10.1002/qj.3688.

Brooks, J. et al., 2019a: Vertical and horizontal distribution of submicron aerosol chemical composition and physical characteristics across northern India during pre-monsoon and monsoon seasons. *Atmospheric Chem. Phys.*, 19: 5615-5634. https://doi.org/10.5194/acp-19-5615-2019.

Brooks, J. et al., 2019b: Black carbon physical and optical properties across northern India during pre-monsoon and monsoon seasons. *Atmospheric Chem. Phys.*, 19: 13079-13096. https://doi.org/10.5194/acp-19-13079-2019.

Chakraborty, T. et al., 2019: Biases in Model-Simulated Surface Energy Fluxes During the Indian Monsoon Onset Period. *Boundary-Layer Meteorol.*, 170: 323-348. https://doi.org/10.1007/s10546-018-0395-x.

Fletcher, J.K. et al., 2020: The dynamic and thermodynamic structure of the monsoon over southern India: New observations from the INCOMPASS IOP. *Q. J. R. Meteorol. Soc.*, 146: 2867-2890. https://doi.org/10.1002/qj.3439.

George, J.V. et al., 2019: Mechanisms of Barrier Layer Formation and Erosion from In Situ Observations in the Bay of Bengal. *Journal of Physical Oceanography*, 49: 1183-1200. https://doi.org/10.1175/JPO-D-18-0204.1.

Hunt, K.M.R. et al., 2020: Modes of coastal precipitation over southwest India and their relationship to intraseasonal variability. *Q. J. R. Meteorol. Soc., online*, https://doi.org/10.1002/qj.3913.

Jayakumar, A. et al., 2020: Performance of the NCMRWF convection-permitting model during contrasting monsoon phases of the 2016 INCOMPASS field campaign. *Q. J. R. Meteorol. Soc.*, 146: 2928-2948. https://doi.org/10.1002/qj.3689.

Kompalli, S. K. et al., 2020: Seasonal contrast in size distributions and mixing state of black carbon and its association with PM1.0 chemical composition from the eastern coast of India. *Atmospheric Chem. Phys.*, 20: 3965-3985. https://doi.org/10.5194/acp-20-3965-2020.

Lewis, H. W. et al., 2019: The UKC3 regional coupled environmental prediction system. *Geoscientific Model Development*, 12: 2357-2400. https://doi.org/10.5194/gmd-12-2357-2019.

Manoj, M. R. et al., 2020: Vertical profiles of submicron aerosol single scattering albedo over the Indian region immediately before monsoon onset and during its development: research from the SWAAMI field campaign. *Atmospheric Chem. Phys.*, 20: 4031-4046. https://doi.org/10.5194/acp-20-4031-2020.

Martin, G. M. et al., 2020: Forecasting the monsoon on daily to seasonal time-scales in support of a field campaign. *Q. J. R. Meteorol. Soc.*, 146: 2906-2927. https://doi.org/10.1002/qj.3620.

Menon, A. et al., 2018: Modelling the moistening of the free troposphere during the northwestward progression of Indian monsoon onset. *Q. J. R. Meteorol. Soc.*, 144: 1152-1168. https://doi.org/10.1002/qj.3281.

Parker, D. J. et al., 2016: The interaction of moist convection and mid-level dry air in the advance of the onset of the Indian monsoon. *Q. J. R. Meteorol. Soc.*, 142: 2256-2272. https://doi.org/10.1002/qj.2815.

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Am. Meteorol. Soc.*, 100: 2509-2532. https://doi.org/10.1175/BAMS-D-17-0330.1.

Sanchez-Franks, A. et al., 2018: Intraseasonal Variability of Air-Sea Fluxes over the Bay of Bengal during the Southwest Monsoon. *J. Clim.*, 31:7087-7109. https://doi.org/10.1175/JCLI-D-17-0652.1.

Sheehan, P. M. F. et al., 2020: Injection of Oxygenated Persian Gulf Water into the Southern Bay of Bengal. *Geophysical Research Letters*, 47, e2020GL087773. https://doi.org/10.1029/2020GL087773.

Takigawa, M. et al., 2020: Can Delhi's pollution be affected by crop fires in the Punjab region? *SOLA*, 16: 86–91. https://doi.org/10.2151/sola.2020-015.

Thushara, V. et al., 2019: Vertical distribution of chlorophyll in dynamically distinct regions of the southern Bay of Bengal. *Biogeosciences*, 16: 1447-1468. https://doi.org/10.5194/bg-16-1447-2019.

Turner, A. G., et al., 2020: Interaction of convective organization with monsoon precipitation, atmosphere, surface and sea: The 2016 INCOMPASS field campaign in India. *Q. J. R. Meteorol. Soc.*, 146: 2828-2852. https://doi.org/10.1002/qj.3633.

Vinayachandran, P. N. et al., 2018: BoBBLE: Ocean-Atmosphere Interaction and Its Impact on the South Asian Monsoon. *Bulletin of the American Meteorological Society*, 99: 1569-1587. https://doi.org/10.1175/BAMS-D-16-0230.1.

Vijith, V. et al., 2020: Closing the sea surface mixed layer temperature budget from in situ observations alone: Operation Advection during BoBBLE. *Scientific Reports* 10: 7062. https://doi.org/10.1038/s41598-020-63320-0.

Volonté, A., Turner, A. and Menon, A., 2020: Airmass analysis of the processes driving the progression of the Indian summer monsoon. *Q. J. R. Meteorol. Soc.*, 146: 2949-2980. https://doi.org/10.1002/qj.3700.

Willetts, P. D. et al., 2017: The 2015 Indian summer monsoon onset – phenomena, forecasting and research flight planning. *Weather*, 72: 168-175.

The Monsoon Mission Field Campaign in the Bay of Bengal

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The South Asian monsoon nourishes rivers, forests, agriculture and human life over vast tracts of the tropics and arid subtropics. Summer monsoon winds, clouds and rainfall in the Indian Ocean region have aperiodic intraseasonal oscillations (ISO): A northeastward moving 30-60 day mode, and a westward propagating quasi-biweekly (7-25 day) mode originating in the equatorial Pacific Ocean. Monsoon ISO involve active air-sea interaction. For instance, the spatial gradient of sea surface temperature (SST) across the Bay of Bengal (Fig. 1, Mahadevan et al., 2016) influences the coherence, recurrence time and northward movement of monsoon rain bands (Sengupta et al., 2001, Vecchi and Harrison, 2002, Shankar et al., 2007). Present-day climate models do not realize the potential predictability of monsoon ISO (Lau et al., 2012), in part because model surface fluxes, as well as upper ocean temperature, salinity and mixing are not realistic.

Climate models rely on semi-empirical “parameterization” of physical processes at unresolved scales. Our knowledge of fine-scale physical processes in the monsoon atmosphere and ocean is inadequate, however, due to the lack of sustained *in situ* observations and limitations of satellite measurements through deep clouds and rainfall. The premise of Monsoon Mission’s Ocean Mixing and Monsoon (OMM; 2014-2020) field campaign in the Bay of Bengal was that high-resolution measurements would lead to new knowledge of ocean physics, particularly sub-mesoscale physical processes at order 1-10 km spatial scales. Measurements of air-sea surface fluxes and extensive upper ocean observations from ships and autonomous instruments were carried out in the field phase (Fig. 1).

With support from the Ministry of Earth Sciences (MoES) and the National Monsoon Mission, the Bay of Bengal field campaign brought together organizations with a tradition of operations and research in monsoon and ocean physics: NIOT, INCOIS, CSIR-NIO and ISRO-SAC, in partnership with TIFR-ICTS, IIT Madras and IISc Bangalore (coordinating Institution). Joint teaching and research between OMM and USA’s ASIRI and MISO-BoB campaigns continues to enrich knowledge of the Bay of Bengal and monsoon air-sea interaction. The main objectives of OMM were to generate a legacy dataset based on high-resolution measurements in the northern Bay of Bengal from research ships and autonomous instruments; accurately measure air-sea surface fluxes of

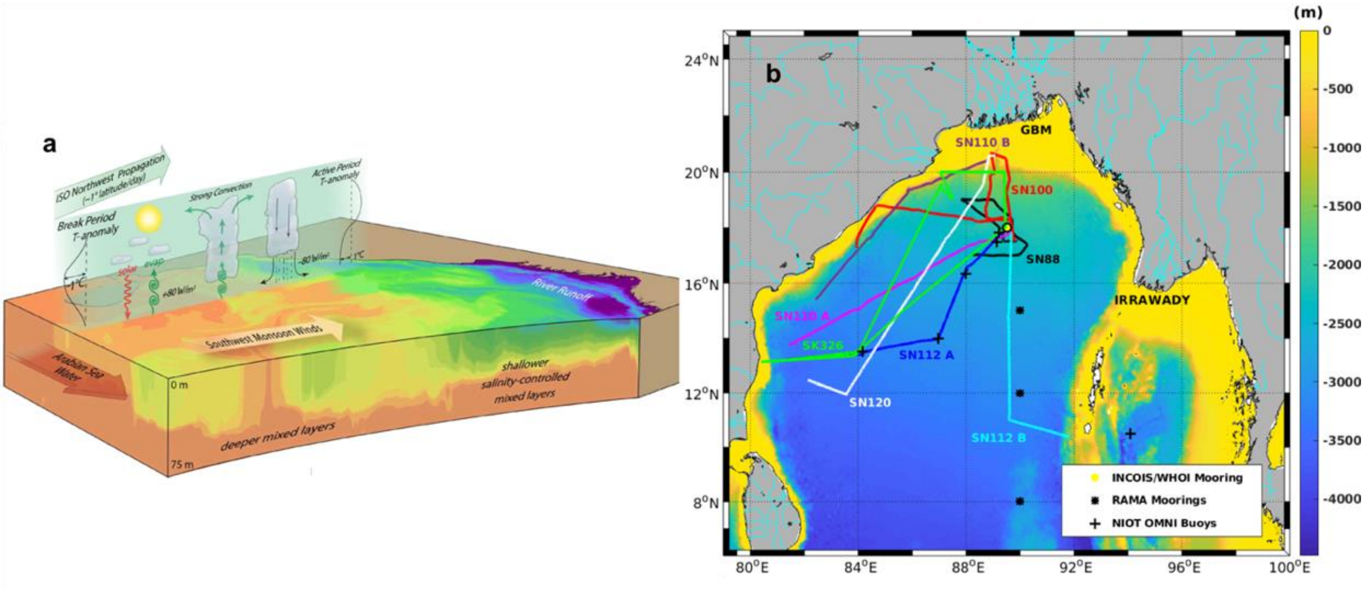

Fig. 1: (a) Schematic of summer monsoon ISO and Bay of Bengal salinity (colour, lowest salinities in purple); net surface heat flux goes from -80 to +80 W/m^2 during the active and quiescent phases of the summer monsoon [Figure courtesy: Emily Shroyer, adapted from Mahadevan et al. 2016]. (b) Bay of Bengal ETOPO2 bathymetry (colour; m); tracks of Sagar Nidhi cruises SN88, SN100, SN110 A and B, SN112 A and B, and Sagar Kanya cruise SK326 are overlaid. Ganga-Brahmaputra-Meghna (GBM) and Irrawady rivers (cyan); INCOIS and WHOI moorings (yellow dot), RAMA moorings (*) and NIOT moorings (+) are marked.

momentum, heat and moisture from moorings; gather fine-scale observations of the subsurface ocean from moorings, ocean gliders and water-following Lagrangian floats, and build institutional capacity in new measurements and analysis.

OMM observations have led to deeper understanding of important phenomena and revealed fine-scale three-dimensional physical processes in the upper ocean: (1) Momentum input from monsoon winds is trapped in a thin surface layer of low-salinity water (river water for simplicity), giving rise to swift "Ekman" currents. (2) Variable Ekman flow associated with the quasi-biweekly monsoon mode and embedded low-pressure systems leads to changes in the spatial distribution of river water and coastal sea level in a matter of days. (3) Sub-mesoscale (order 1-10 km) salinity-dominated fronts are common in the north Bay of Bengal; mixed layer depth is shallow at the fronts, likely due to slumping. (4) Moored observations show that turbulence in the subsurface ocean is suppressed under river water, probably due to inhibition of downward energy transport by wind-generated near-inertial waves. (5) Order 100 km-scale eddies drift from the Andaman Sea to the central Bay of Bengal, while retaining temperature/salinity properties at thermocline depths. (6) Episodic surface buoyancy loss from the north bay leads to vertical mixing of the upper ocean to 40-60 m depth in winter. (7) The shallow, salinity-dominated stratification and a deep subsurface warm layer lead to fundamental changes in the response of Bay of Bengal SST to tropical cyclones and monsoon ISO. We refer the reader to collected articles in the book "Observing the oceans in real time" (Venkatesan et al., 2018), and special issues of Oceanography (Mahadevan et al., 2016) and Deep-Sea Research (Gordon et al., 2019, 2020).

From August to January, much of the open ocean in the north Bay of Bengal is covered by a 1-10 m deep surface layer of very low salinity (21-31 psu) water from summer monsoon rain and river runoff. The availability of Sea surface salinity (SSS) data from satellite microwave sensors in recent years is a major step forward in oceanography. The movement of Ganga-Brahmaputra-Meghna (GBM) river water is clearly seen in SSS from the SMAP satellite (Fig. 2a). River water is stirred into the interior and dispersed by order 100 km mesoscale ocean eddies, and a shallow wind-driven flow. In August-September 2015, the flow between an anticyclonic eddy (centre near 19°N 88°E) and a cyclonic eddy to the east draws river water to the interior. Surface salinity gradient at the western edge of the river water is 6 psu in 100 km in satellite SSS, and 6 psu in 65 km in underway CTD (uCTD) measurements from the ship (Fig. 2b). As the ship crosses the eddy during cruise SN100, surface wind stress strengthens to the east of 89.5°E (about 320-450 km along track); shallow currents measured from shipborne ADCP have an enhanced eastward wind-forced "Ekman" component in addition to the geostrophic flow at deeper levels (Fig. 2b,c). Moored measurements show that a shallow, directly wind-forced Ekman current with speed reaching 0.4 m/s disperses river water to the north and east during the 2015 summer monsoon season (not shown). Moored surface wind stress and salinity show distinct variability at 7-25 day periods, and coastal sea level rises and falls by 0.1-0.5 m in response to changing winds associated with the quasi-biweekly monsoon

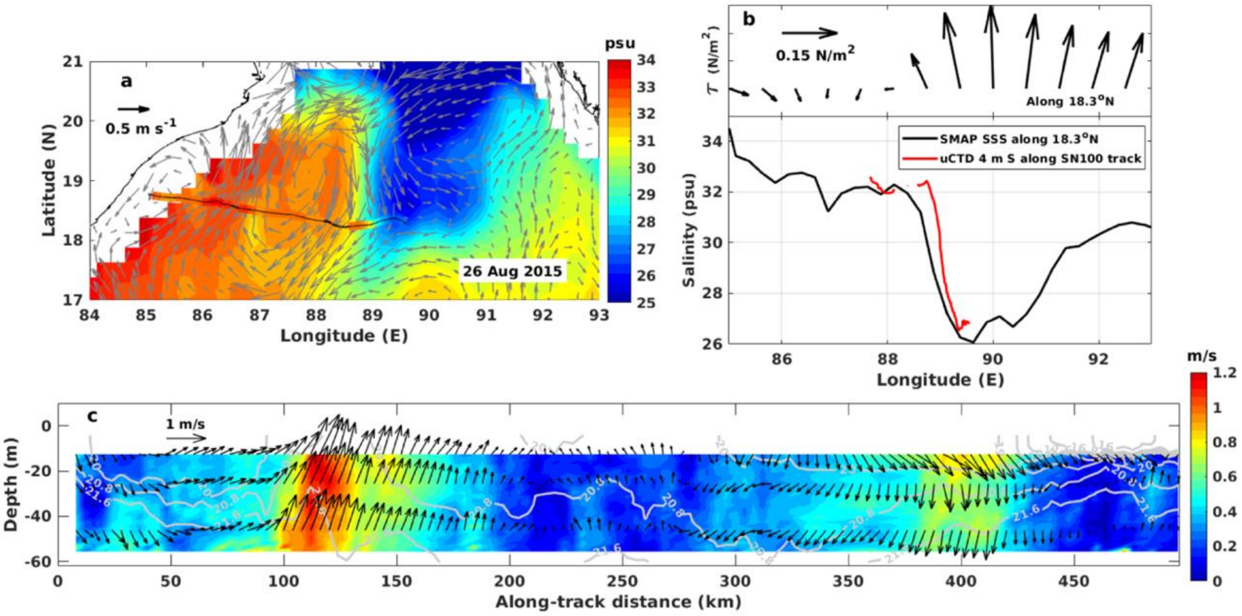

Fig. 2: River water and geostrophic eddies in the northern Bay of Bengal. (a) Eight-day running mean sea surface salinity (SSS; psu) from the Soil Moisture Active-Passive (SMAP) satellite mission (colour) and AVISO surface geostrophic currents (m/s; vectors) on 26 August 2015. ORV Sagar Nidhi cruise SN100 salinity (psu) at 4 m depth (colour) from underway CTD (uCTD) across the anticyclonic eddy, 25 August 15:35 UTC to 28 August 01:30 UTC. (b) Daily surface wind stress from MERRA2 reanalysis (τ, N/m^2; vectors); SMAP SSS (black) along 18.3°N on 26 August, and 4 m salinity from uCTD (red). (c) Horizontal velocity (m/s; vectors) at 12.5, 25 and 46 m depth, and current speed (m/s; colour) from hull-mounted RDI 300 kHz Acoustic Doppler Current Profiler (ADCP) as a function of distance (km); contours of potential density (σ_θ kg/m^3; grey). Horizontal resolution of ADCP and uCTD data is 300 m to 1000 m. σ_θ contour interval is 0.8 kg/m^3, 16.0-21.6 kg/m^3. Reference vectors are shown for (a, c) ocean currents (0.5 m/s and 1 m/s), and (b) wind stress (0.15 N/m^2).

mode and embedded weather systems (Sree Lekha et al., 2020).

Observations in the north bay consistently show a warm, nearly isothermal subsurface layer (i.e., barrier-layer) in the presence of river water in autumn and winter. The shallow river water influences upper ocean temperature in at least two ways: First, the thin surface mixed layer cools and warms more rapidly in response to changing surface heat flux. Second, a substantial fraction (upto 30%) of incident shortwave radiation penetrates below the thin mixed layer, warming the subsurface ocean to 60-80 m depth. The first direct measurements of ocean turbulence from fast-response thermistors (chi-pods) on the WHOI mooring at 18°N show a remarkable reduction of subsurface temperature diffusivity under the shallow layer of river water (Fig. 3; Thakur et al., 2019). ADCP observations from NIOT moorings reveal inhibition of vertically propagating near-inertial waves under river water (Chaudhuri et al., in preparation). The quenching of subsurface turbulence can aid the formation of a subsurface warm layer by inhibiting vertical mixing with cool upper thermocline water.

Sub-mesoscale (order 1-10 km) variability of salinity, density and currents is common in the north Bay of Bengal in all seasons (Sengupta et al., 2016, MacKinnon et al., 2016, Sarkar et al., 2016). River water is stirred and drawn into filaments by the mesoscale ocean eddy field, sharpening lateral gradients between low-salinity water and saltier seawater. High-resolution measurements on OMM cruises SN88 and SN100 in August-September 2014 and 2015 show numerous shallow, salinity-dominated density fronts (see Fig. 4) with lateral scales of 3-25 km, net cross-front density change of 0.3-1.5 kg/m^3, and Rossby number (ratio of relative vorticity to Coriolis frequency) close to one. Slumping (tilting of isopycnals) at intense sub-mesoscale fronts restratifies the near-surface ocean on time scales of a day (Pollard and Regier, 1992, Ramachandran et al., 2018). In general, OMM observations show shallow mixed layers associated with strong lateral density gradients (two examples are shown in Fig. 4b,d). Ekman flow forced by southwesterly monsoon winds tends to drive denser water over lighter water on the western edge of fronts, promoting turbulent deepening of the mixed layer (Fig. 4c; D'Asaro et al., 2011). In addition to surface heat and freshwater gain, lateral sub-mesoscale processes sustain near-surface stratification in the Bay of Bengal.

Finally, we note two results of immediate practical interest. Pre-monsoon tropical cyclone Roanu (2016) had modest strength but led to widespread cooling of SST by 1.5-2°C. Detailed measurements from a profiling Lagrangian float

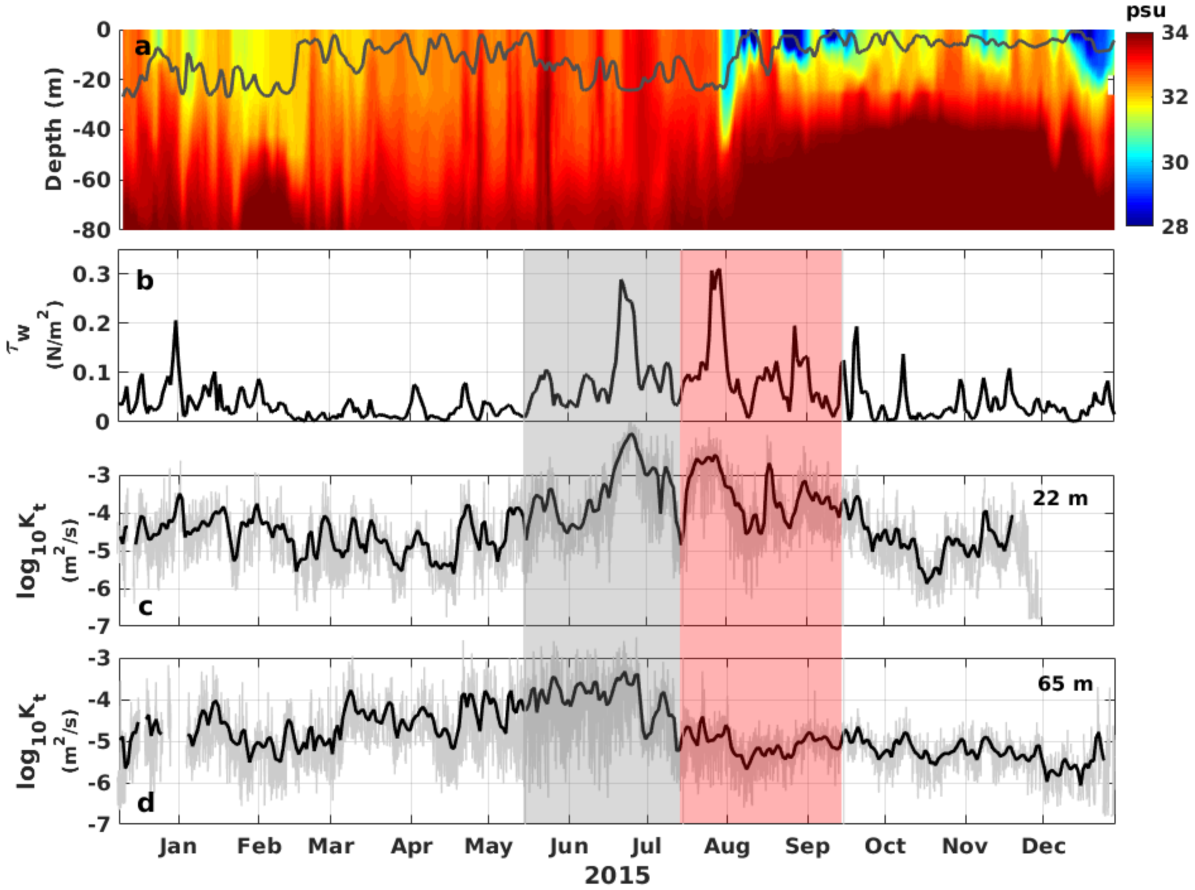

Fig. 3: Subsurface turbulence is suppressed when river water arrives at the Woods Hole Oceanographic Institution (WHOI) mooring (18.01°N 89.45°E). (a) Daily mean salinity (psu; colour) from December 2014 to December 2015, and depth of mixed layer (MLD; m, gray line) where σ_θ exceeds surface σ_θ by 0.125 kg/m^3. (b) Daily wind stress (τ_w ; N/m^2) at 10m height. (c, d) Hourly (thin gray) and daily (thick black) thermal diffusivity $\log_{10}K_t$ (m^2/s) from chi-pod measurements at (c) 22 m and (d) 65 m depth. Early and late summer monsoon are shaded: 15 May-15 July 2015 (gray) and 15 July-15 September 2015 (red). The median values of $\log_{10}K_t$ at 65m are -3.89 m^2/s and -5.09 m^2/s during early and late summer monsoon (Adapted from Thakur et al., 2019).

reveal shear-induced mixing reaching 65 m under the cyclone, nearly twice the depth of the mixed layer (Kumar et al., 2019). On the other hand, the stable salinity-dominated stratification and deep subsurface warm layer lead to minimal SST cooling, even under intense post-monsoon cyclones in the northern Bay of Bengal. Guided by observations from INCOIS and NIOT moorings, simple models suggest that the maximum sustained windspeed in cyclone Phailin (October 2013) were enhanced by nearly 5 m/s (8%) due to the absence of SST cooling by storm-induced mixing (Chaudhuri et al., 2019). Intense anticyclonic mesoscale eddies in the western bay (e.g., Fig. 2) have deep warm cores and significantly higher dissolved oxygen levels at 100-500 m depth than in the ambient oxygen minimum zone or in cyclonic eddies (Sarma et al., 2018), and may help mitigate the feared “dead zones” in this basin in the coming decades.

Surface freshwater has important effects on Bay of Bengal SST by enhancing near-surface salinity stratification and shallowing the mixed layer; as a result, momentum input from surface wind stress is trapped in a shallow surface layer; heat and momentum fluxes to the deeper ocean are substantially modified; subsurface turbulence is quenched, and deep mixing is reduced. Sub-mesoscale ocean processes involving lateral salinity gradients influence the thermodynamic state of the upper ocean by directly enhancing and sustaining shallow stratification. Most global coupled models have significant biases in the simulation of Bay of Bengal SST, as well as monsoon rainfall and variability. Recent experiments with high-resolution regional models indicate that intense rainfall from relatively small-scale organised monsoon convection is sensitive to the spatial patterns of ocean mixed layer depth, SST and 10-100 km-scale SST gradients in the north Bay of Bengal (Samanta et al., 2018). Interestingly, satellite data indicate that SST gradients are readily in the north bay created by advective stirring of river water by surface currents (Mathur et al., 2019). Realistic representation of upper ocean processes in this river-dominated basin appears to be an essential element in the quest for improved monsoon forecasts on weather to climate scales. In the coming decades, sustained observations of the ocean and atmosphere from autonomous instruments (Venkatesan et al., 2018) would make a real impact in the data-poor coastal regions.

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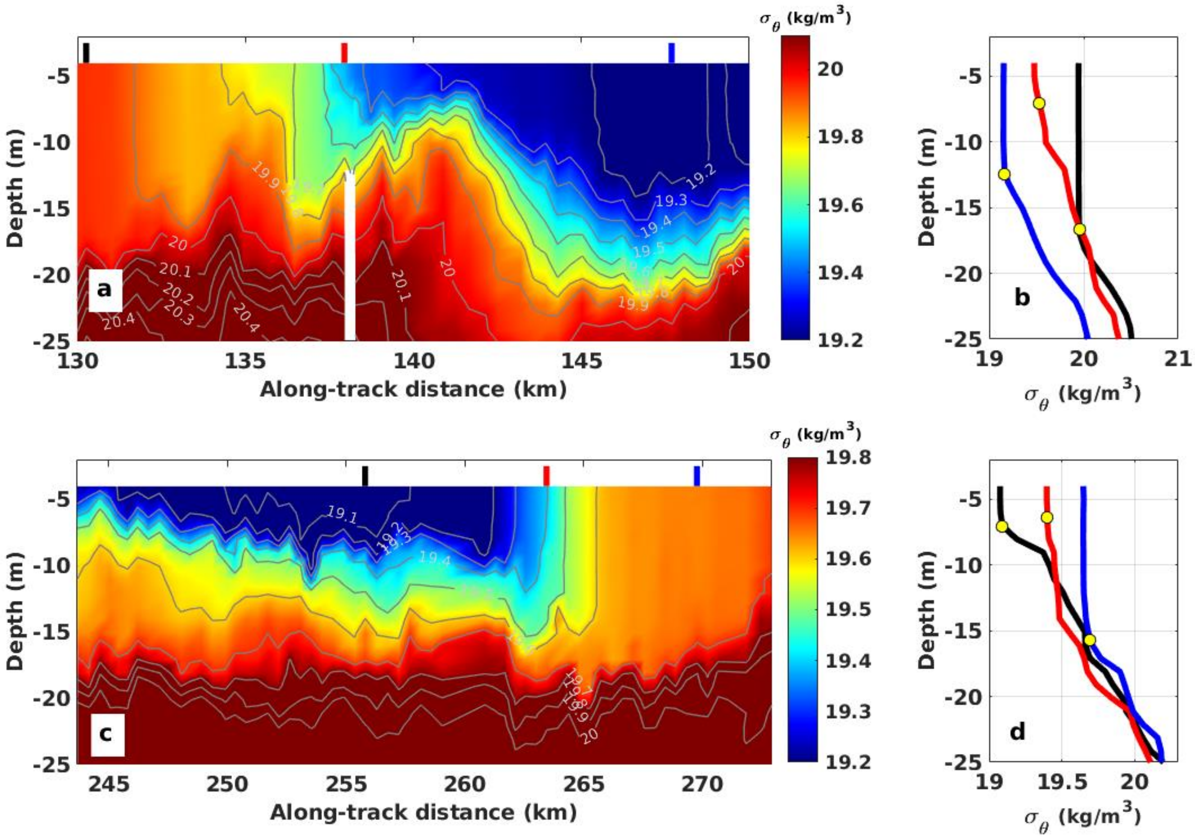

Fig. 4: Density structure at sub-mesoscale (order 1-10 km) fronts. (a) Depth-distance plot of potential density anomaly (σ_θ ; kg/m^3; colour and contours) from uCTD on 28 August 2014 as the ship moved from west to east during cruise SN88. (b) Vertical profiles of σ_θ at the front (red bar) and on either side (blue and black bars). Mixed layer depth (MLD), defined as the depth where σ_θ exceeds σ_θ at 4 m depth by 0.03 kg/m^3, is marked by yellow dots. (c,d) as in (a,b), but for another front as the ship moved from east to west. In both cases, the mixed layer is shallower at the front relative to either side.

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References:

Chaudhuri, D. et al., 2019: Response of the salinity-stratified Bay of Bengal to cyclone Phailin. *J. Phys. Oceanogr.*, 49(5), 1121-1140.

D'Asaro, E.A. et al., 2011: Enhanced turbulence and energy dissipation at ocean fronts. *Science*, 332(6027), 318-322.

Gordon, A.L. et al., 2019: Introduction to Atmosphere-Ocean Dynamics of Bay of Bengal. Volume 1. *Deep-Sea Res. Part II*, 168, 104670.

Gordon, A.L. et al., 2020: Introduction to Atmosphere-Ocean Dynamics of Bay of Bengal. Volume 2. *Deep-Sea Res. Part II*, 172, 104724.

Lau, W.K., Waliser, D.E. and Goswami, B.N., 2012: South Asian monsoon. In *Intraseasonal variability in the atmosphere-ocean climate system*, 21-72. Springer.

Mahadevan, A. et al., 2016: Introduction to the special issue on the Bay of Bengal: From monsoons to mixing. *Oceanography*, 29(2), 14-17.

MacKinnon, J.A. et al., 2016: A tale of two spicy seas. *Oceanography*, 29(2), 50-61.

Mathur, M. et al., 2019: Thermal fronts and attracting Lagrangian Coherent Structures in the north Bay of Bengal during December 2015-March 2016. *Deep Sea Res. Part II*, 168, 104636.

Pollard, R.T. and Regier, L.A., 1992: Vorticity and vertical circulation at an ocean front. *J. Phys. Oceanogr.*, 22(6), 609-625.

Kumar, B.P., D'Asaro, E. and Ravichandran, M., 2019: Widespread cooling of the Bay of Bengal by tropical storm Roanu. *Deep Sea Research Part II*, 168, 104652.

Ramachandran, S. et al., 2018: Sub-mesoscale processes at shallow salinity fronts in the Bay of Bengal: Observations during the winter monsoon, *J. Phys. Oceanogr.*, 48(3), 479-509.

Samanta, D. et al., 2018: Impact of a Narrow Coastal Bay of Bengal Sea Surface Temperature Front on an Indian Summer Monsoon Simulation, *Scientific reports*, 8(1), 17,694.

Sarkar, S. et al., 2016: The interplay between submesoscale instabilities and turbulence in the surface layer of the Bay of Bengal, *Oceanography*, 29(2), 146-157.

Sarma, V.V.S.S. et al., 2018: Role of eddies on intensity of oxygen minimum zone in the Bay of Bengal. *Cont. Shelf Res.*, 168, 48-53.

Sengupta, D. and Ravichandran, M., 2001: Oscillations of Bay of Bengal sea surface temperature during the 1998 summer monsoon. *Geophys. Res. Lett.*, 28(10), 2033-2036.

Sengupta, D. et al., 2016: Near-surface salinity and stratification in the north Bay of Bengal from moored observations, *Geophys. Res. Lett.*, 43(9), 4448-4456.

Shankar, D., Shetye, S. and Joseph P.V., 2007: Link between convection and meridional gradient of sea surface temperature in the Bay of Bengal, *J. Earth Syst. Sci.*, 116(5), 385-406.

Sree Lekha, J. et al., 2020: Quasi-biweekly mode of the Asian summer monsoon in Bay of Bengal surface observations. *J. Geophys. Res. Oceans* (In review).

Thakur, R. et al., 2019: Seasonality and Buoyancy Suppression of Turbulence in the Bay of Bengal. *Geophys. Res. Lett.*, 46(8), 4346-4355.

Vecchi, G.A. and Harrison, D.E., 2002: Monsoon breaks and subseasonal sea surface temperature variability in the Bay of Bengal. *J. Clim.*, 15(12), 1485-1493.

Venkatesan, R. et al. (Eds.), 2018: Observing the Oceans in Real Time. *Springer International Publishing*.

India's Monsoon Mission Contributions to Regional Climate Information and Services for South Asia

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1. Introduction

Climate information products, particularly concerning the seasonal rainfall and temperature conditions, are crucial for all the countries of South Asia and depend on the sectoral assets in focus. As major influencers of seasonal climate of the region, the South Asian monsoons therefore need to be better understood and predicted with greater confidence. Atmospheric researchers both globally and nationally have been pushing the frontiers of understanding the Asian monsoons, as exemplified by several campaigns such as MONEX (Monsoon Experiment; Das, 1979) and GAME (GEWEX Monsoon Experiment; http://www.hyarc.nagoya-u.ac.jp/game/index.html) which were international, and ARMEX (Arabian Sea Monsoon Experiment; Rao, 2005), BoBMEX (Bay of Bengal Monsoon Experiment; Yihui Ding, 2007), MONTBLEX (Monsoon Trough Boundary Layer Experiment; Rao, 2019) and LASPEX (Land Surface Processes Experiment; Vernekar et al., 2003) that were coordinated nationally. Climate information services in South Asia are enabled by research and development initiatives undertaken and the current Monsoon Mission (MM) has furthered this through its objectives to improve monsoon predictions at all time scales, particularly the extended range (up to 20 days).

Ideal climate services are driven by reliable predictions that become well-trusted and more demanded by users. Agile approaches to translate research into operational services are required to inform decisions that can reduce risks and losses. Equally important is to understand the uncertainties in the climate information and adopt strategies to deal with these uncertainties in specific user contexts. Operationalizing systematic use of such information also requires a well-coordinated end-to-end institutional system that begins with monitoring and generation of climate information of high quality and ends with a community level response.

The main challenge of establishing a system for generating applied climate information is the customization of information to specific decision-making levels. This needs to be evolved iteratively through stakeholder engagement. It is also important to build capacities and awareness among stakeholders on an ongoing basis with close coordination across government departments from local to national levels.

Improving climate services and its delivery is critical to South Asia as climate change projections indicate with high confidence that the frequency and intensity of monsoon extreme rainfall events will increase resulting in higher risks of droughts and floods (Wang et al., 2020). The Regional Integrated Multi-hazard Early-warning System (RIMES), supported by the World Meteorological Organization (WMO) and working in close collaboration with the WMO Regional Climate Centre (RCC) Pune hosted by the India Meteorological Department (IMD), started implementing the Global Framework Climate Services (GFCS) in South Asia during 2016-18 under the Programme for Implementing the GFCS at Regional and National Scales funded by the Environment and Climate Change Canada. This work is now being further improved in collaboration with the United Kingdom Met Office (UKMO) under the Asia Regional Resilience to Changing Climate (ARRCC) Programme with support from the UK Aid since November 2018.

This article outlines the implementation of climate services in South Asia region, highlighting linkages with research and development efforts such as MM that enabled enhanced generation of regionally relevant climate information and also emphasizes the importance of sustaining such efforts for the benefit of the region.

2. Improved systems for seasonal and sub-seasonal predictions

Credible climate information is one of the important elements in the decision-making matrix for effective climate risk management. The Climate Services Information System (CSIS) is the operational backbone of GFCS and a principal mechanism to routinely collate, store, process information about past, present, and future climates and make it available from global to regional to national levels to support climate services around the world. Global and regional centers and National Meteorological and Hydrological Services (NMHSs) provide climate service products to be used at the country level to support more effective adaptation. The WMO Global Producing Centers for Long Range Forecasts (GPCs-LRF) routinely produce and disseminate a wide range of seasonal climate predictions on the global scale, including verification and other products based on information from nationally operated observing networks. The WMO Lead Centre for Long-Range Forecast Multi-Model Ensemble (LC-LRFMME; https://www.wmolc.org/) consolidates and facilitates access to the products from GPCs-LRF and also produces operational MME forecasts.

The WMO RCCs are mandated to generate and deliver more regionally focused high-resolution data and products through contextualizing the global products for the region, and support training and capacity building within the region to interpret such results from a national perspective. RCC-Pune serves as a WMO RCC for South Asia region. It uses the coupled forecasting system (CFS) model developed under MM programme at the Indian Institute of Tropical Meteorology (IITM). Monthly and seasonal forecasting products from the high resolution ~38km (T382L64) 10-member ensemble suite have been used operationally by IMD since January 2017.

MM has helped in meeting the demand of NMHSs and sectoral users in South Asia for sub-seasonal forecast updates made through the Extended Range Prediction (ERP) system (Sahai et al., 2013 & 2015; Borah et al., 2015). The details of ERP system are also outlined by Surya et al. (2020). The ERP system is being used to generate various weekly forecast products for the next four weeks operationally, which are made available online (https://www.tropmet.res.in/erpas/). These products include weekly mean and anomaly spatial distribution of rainfall, maximum and minimum temperatures, mean sea level pressure, Madden Julian Oscillation (MJO), Monsoon Intraseasonal Oscillation (MISO), cyclone genesis over Indian Ocean, and others. The extended range forecasts have significant importance for the decision-making processes in climate sensitive sectors like agriculture, hydrology, energy, health etc. Some of the ERP based applications already implemented are (i) preparation of agromet advisories for supporting agriculture activities such as sowing, irrigation scheduling, applying pesticides and fertilizers, and harvesting; (ii) heat action plan based on prediction heat waves in major urban cities (iii) health advisories for vector borne diseases such as dengue fever, malaria, and others; and (iv) water level management of dams.

3. Regional and National Climate Forums

The Regional Climate Outlook Forums (RCOFs; WMO, 2016) serve as platforms to bring together climate experts and stakeholders to produce regional-scale climate outlook for the main seasons of interest to the region. The regional outlooks provide valuable guidance for national climate outlooks which are prepared considering the specific features that influence climate in a national domain. The RCOFs are recognized as a key component of CSIS and serve as user interface platforms at a regional level to understand users' needs and enhance the use of climate information.

South Asian Climate Outlook Forum and User Engagement

The South Asian countries (Afghanistan, Pakistan, India, Nepal, Bhutan, Bangladesh, Myanmar, Sri Lanka and Maldives), supported by WMO, came together to establish the South Asian Climate Outlook Forum (SASCOF) in 2010. Climate information flow within the GFCS implementation over South Asia, with SASCOF playing a central role in regional coordination, is depicted in Fig. 1. In SASCOF sessions the available global operational products, including from WMO LC-LRFMME, are considered in formulating the seasonal climate outlooks. Right from the outset, SASCOF sessions have received overwhelming support from all the South Asian countries and have been initially organized every year before the summer monsoon season. These sessions were preceded by training workshops to enhance capacities of NMHSs climate experts to generate seasonal climate outlooks. RCCs in the region and a number of GPC LRFs provided support in terms of their products and resource persons. RCC-Pune plays a lead role in organizing training workshops as well as SASCOF sessions in close coordination with RIMES. The South Asian NMHSs take turns in hosting and organizing the SASCOF sessions. For the first time, the SASCOF session for summer

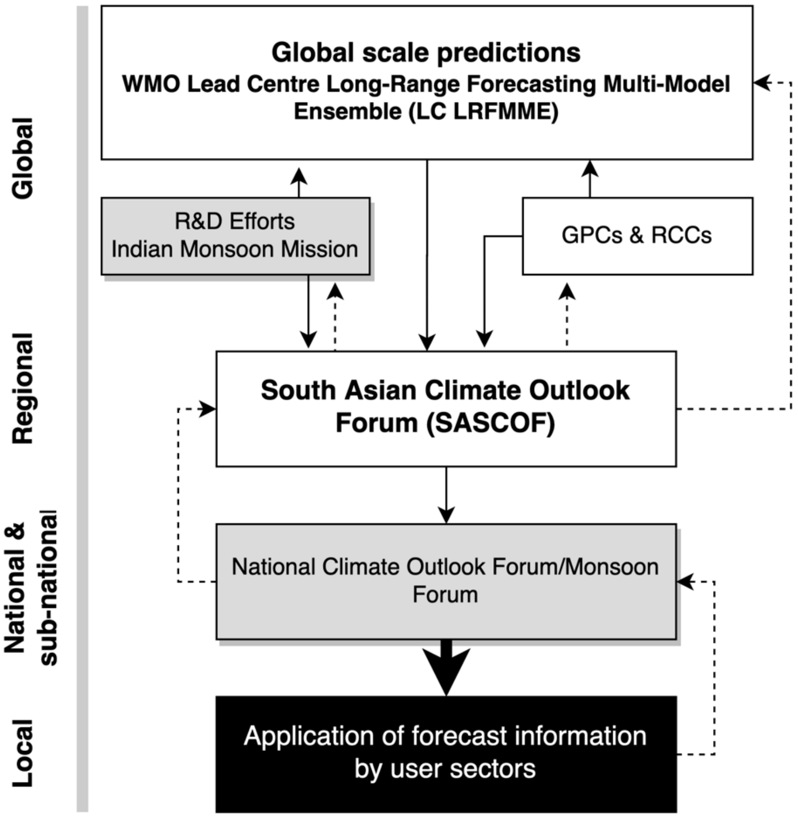

Fig. 1: Climate information flows from global to local levels within the GFCS implementation in South Asia facilitated by WMO Global Producing Centers for Long Range Forecasts (GPCLRFs) and Regional Climate Centers (RCCs) supported by the Indian Monsoon Mission. Dotted arrows indicate feedbacks to improve and customize information.

monsoon of 2020 was held virtually due to COVID-19 related travel restrictions and safety guidelines.

The crucial role of winter rains and the growing recognition of the benefits of SASCOF sessions in sharing seasonal climate outlooks led to the need for also conducting a winter SASCOF session leveraging available project funding. The first winter SASCOF session (SASCOF 7) was organized in close collaboration with IMD in Chennai, Tamil Nadu, India in October 2015. Since then, SASCOF sessions have been held twice a year, in April prior to the summer monsoon season (June to September), and in September targeting the winter season (October to December).

The SASCOF sessions also started featuring Climate Services User Forums (CSUF), aimed to bring together user agencies from both regional and national levels to discuss potential planning and preparedness based on seasonal outlooks. CSUFs also facilitate feedback for improvement of climate information. At a regional level, the SASCOF climate outlooks seem to capture the overall rainfall status of the whole season. Users, however, have expressed their need for additional details like the date of start of the rains and their variations within the season, which are not currently available as part of seasonal predictions, and require further research and joint efforts to transition research results to operational practice.

National Climate Outlook Forum (NCOFs)

NCOFs serve as national platforms for regular dialogue among climate service providers and stakeholders seeking improved societal outcomes associated with natural hazards, climate variability, extremes, and change (Fig. 2). Such a dialogue process involves the continuous cycle of forecast generation, dissemination, application, and evaluation of application results. The NCOFs focused on understanding climate risks and orienting users to climate information products available from NMHSs, guiding users on application of these products in analyzing potential sectoral impacts, and need for inter-agency coordination for managing these potential impacts. At present NCOFs/Monsoon Forums are being regularly conducted in almost all countries in South Asia.

NCOF participating sectoral agencies in many countries have consistently recommended the forum to be conducted

Fig. 2: User sector representatives interpreting seasonal climate outlook at a NCOF (Monsoon Forum) session in Dhaka, Bangladesh.

regularly around the key seasons. They also require periodic updates of the seasonal outlooks and sub-seasonal scale forecasts at weekly intervals. Users have also expressed a need for derived forecast products like monsoon onset and withdrawal dates. In many instances, well-validated and authentic historical climate information was sought which shows the wide range of user requirements. NCOFs often serve as a starting point for long-term interactions with priority user sectors of the government like agriculture, water resources, health, and disaster risk management. NCOFs discussions tend to span a wider range of weather and climate information such as climate change and day-to-day weather predictions and at times even traditional knowledge sources and beliefs.

Towards improved SASCOF processes

WMO has recently developed a project proposal on strengthening the CSIS on sub-regional scales (CSIS-R), focused on the operationalization of objective seasonal forecasts, and tailored products on sub-regional scales, and country-level service delivery. This system will provide step-by-step guidance based on sub-regional experience in transitioning from subjective and consensus-based seasonal outlooks practices of RCOFs into more traceable and reproducible objective seasonal predictions, based on multi-model ensembles from dynamical climate models. The proposal is grounded on the newly released WMO guidance on operational practices for objective seasonal forecasting (WMO, 2020). Priority steps outlined for transitioning to a more objective procedure to generate seasonal climate information include:

1. Identify and use standard observational datasets and reference periods for calibration and verification of climate prediction models used to generate regional and national climate outlooks.
2. Select General Circulation Models (GCMs) for use in the multi-model ensemble based on their performance over the region. This requires robust assessment of GCM skills over the region including their relative ability to simulate key drivers of seasonal and sub-seasonal climate over the region.
3. Identified calibration/downscaling approach and enabling tools that facilitate operational use, informed by understanding and documentation of national climate context along with its linkages to regional and global climate drivers.
4. Monthly update of climate outlooks by respective RCC's responsible, and providing access to digital data on regionally optimized prediction products
5. Expert appraisals of regional climate information products with standard verification procedures leading to refinement cycles. Regional guidelines to be evolved for each RCOF and implemented by coordinating RCCs.

Improving user interface

1. Use standardized template for regional climate outlook statement to be issued:
    a. Evolve user interface process to be held in conjunction with SASCOF sessions;
    b. Co-development, co-design, communication, outreach (including a variety of templates for presenting the outlook for public at the regional as well as national levels);
    c. Include communication of uncertainties.
2. Operationalization of priority tailored products to be introduced:
    a. Initiate the process of equipping NMHSs to routinely generate forecasts of key variables and/or exceedance probabilities of key thresholds;
    b. Identify key variables and thresholds through use-oriented, user-driven workshops to define specifications for tailored products needed to support decision-making in specific priority sectors (e.g., reservoir inflow forecasts for hydropower, vegetation indices for pasture management, rainfall or temperature threshold exceedance probabilities for particular crops important in each ecological sub-region, etc.).

4. Concluding Remarks

The MM programme has made significant contributions to regional climate services in South Asia through the addition of climate data at seasonal and sub-seasonal scales from the CFS operational in RCC-Pune. The research work during the first phase of the MM programme provides scientific guidance to support the transition to an objective seasonal climate outlook generation process. MM research studies have also pointed out shared problems among climate models in their simulation of the South Asian summer monsoon (Rao et al., 2019). Although the rainfall teleconnections with the El Niño/Southern Oscillation associated sea surface temperatures are picked up with good skill, models are unable to simulate Indian Ocean Dipole (IOD) linked rainfall teleconnections. Other issues include biases in the seasonal mean precipitation, circulation climatologies and simulation of sub-seasonal variability. Further research work under MM can help resolve problems and improve model skills. Understanding the role of regional climate drivers on national scale will facilitate localization of the products for countries in the region. Application-oriented research being undertaken under the second phase of the Mission will bring further improvements to the user interface for effective climate services in South Asia.

The CLIVAR/GEWEX Monsoons Panel and its regional Working Group on Asian-Australian Monsoon (WG-AAM) with its focus on process based diagnostics for monsoons, assessing predictive skills of climate modelling systems and direct engagement with stakeholders is well aligned to provide research support required for elevating the operational processes of SASCOF to a more science based objective approach. With this view, WG-AAM co-chairs and members have been involved in recent SASCOF sessions and follow-up discussions to evolve research plans have taken place. Continuing on this track will provide robust linkage between research and operations to replicate contributions made by the MM programme to operational seasonal predictions in South Asia.

References

Borah, N. et al., 2015: An assessment of real-time extended range forecast of 2013 Indian summer monsoon. *Int. J. Climatol.*, 35: 2860-2876. doi:10.1002/joc.4178.

Das, P.K., 1979: The Monsoon Experiment (MONEX), *Curr. Sci.,* 48, 187-189.

Ding, Y., 2007: The Variability of the Asian Summer Monsoon, *J. Met. Soc. Japan*, 85B, 21-54.

Rao, S.A. et al., 2019: Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales. *Bull. Am. Meteorol. Soc.*, 100: 2509-2532. https://doi.org/10.1175/BAMS-D-17-0330.1.

Rao, S.A. et al., 2020: Major Achievements of Monsoon Mission. *CLIVAR Exchanges* (this issue).

Rao, N., 2019: MONTBLEX: India's First Major Monsoon Experiment, *CONNECT with the Indian Institute of Science*, 6 (3), 2-5.

Rao, P.S., 2005: Arabian Sea monsoon experiment: An overview, *Mausam*, 56, 1-6.

Sahai A.K. et al., 2015: Real-time performance of a multi-model ensemble-based extended range forecast system in predicting the 2014 monsoon season based on NCEP-CFSv2, *Curr. Sci.*, 109, 1802-1813.

Sahai A. K. et al., 2013: Simulation and extended range prediction of monsoon intraseasonal oscillations in NCEP CFS/GFS version 2 framework. *Curr. Sci.*, Vol. 104, No. 10, 1394-1408.

Vernekar, K.G. et al., 2003: An Overview of the Land Surface Processes Experiment (LASPEX) over a Semi-Arid Region of India. *Boundary-Layer Meteorology* 106, 561-572. https://doi.org/10.1023/A:1021283503661

Wang, B. et al., 2020: Monsoons Climate Change Assessment, *Bull. Am. Meteorol. Soc*., online (https://doi.org/10.1175/BAMS-D-19-0335.1)

WMO, 2016: Regional Climate Outlook Forums (Fact Sheets), World Meteorological Organization, Geneva, Switzerland, https://library.wmo.int/doc_num.php?explnum_id=3191.

WMO, 2020: Guidance on Operational Practices for Objective Seasonal Forecasting, WMO-No. 1246, World Meteorological Organization, Geneva, Switzerland, https://library.wmo.int/doc_num.php?explnum_id=10314.

South Asian Monsoon Climate Change Projections

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1. Introduction

The distribution of summer monsoon precipitation over the South Asian region is closely tied to the annual cycle of solar heating resulting in northward migration of the inter-tropical convergence zone (ITCZ) and setting up of the large-scale southwest summer monsoon circulation (see Krishnamurti and Surgi, 1987; Webster et al., 1998; Gadgil, 2003; Schneider et al., 2014). Climatologically, most areas in South Asia receive more than 75% of the annual rainfall during the June-September months, which has strong bearing on the region's agricultural, industrial and socio-economic activities (Bookhagen and Burbank, 2010; Turner and Annamalai, 2012; Fein and Stephens, 1987; Shige et al., 2017). While the dynamics, variability and predictability of the South Asian monsoon have always been topics of great scientific interest (e.g., Keshavamurty and Sankar Rao, 1992; Webster et al., 1998), there is considerable attention in the recent decades to better understand and quantify how the global and regional monsoon systems would respond to human-induced climate change (Turner and Annamalai, 2012; Rajeevan and Shailesh Nayak, 2017; Wang et al., 2020; Krishnan et al., 2020). This article presents a brief synthesis of the current understanding of the observed and future projected changes in the South Asian monsoon rainfall, based on published literature, including the IPCC AR5 report (2013), and results from the CMIP6 model experiments. Also included in this article is a short discussion on key knowledge gaps pertaining to the monsoon processes, links between precipitation and monsoon circulation changes in a warming climate, challenges in near-term monsoon projection and the need to improve the state-of-the-art climate models for enhancing the reliability of the South Asian monsoon projections.

2. Synthesis of observed and projected changes in the South Asian monsoon

Global and regional monsoon precipitation variations are influenced both by natural and anthropogenic forcing (e.g., IPCC, 2013; Kitoh et al., 2013; Wang et al. 2020). In this section, we provide a synthesis of the past observed changes in the South Asian monsoon and the future projections for the 21st century. The main focus is on changes in the mean summer monsoon precipitation, while precipitation extremes and heavy rainfall events are briefly discussed here. This section also includes a discussion on attribution of the observed monsoon precipitation changes to anthropogenic forcing.

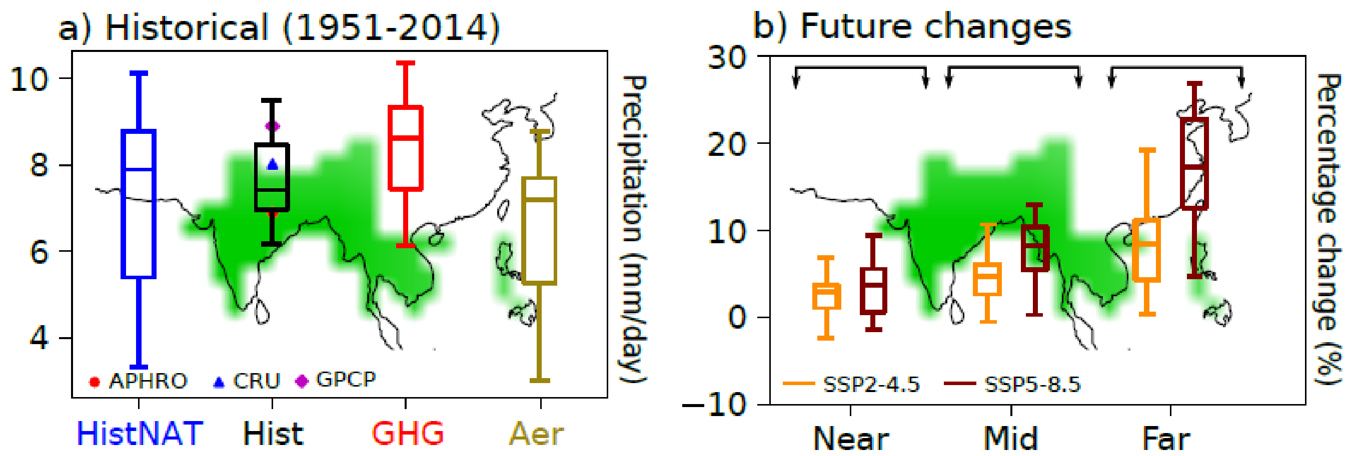

Fig.1: Historical and future projections of South and Southeast Asian monsoon rainfall from CMIP6: *(a)* Box-whisker plots of summer monsoon rainfall for the period (1951-2014) based on 10 CMIP6 models (ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, CESM2, FGOALS-g3, GFDL-ESM4, IITM-ESM, IPSL-CM6A-L, MIROC6, MRI-ESM2-0) over the land region of South and Southeast Asia (green shading, Kitoh et al. 2013). Also shown are the mean monsoon rainfall from the APHRODITE, CRU and GPCP datasets; and attribution analysis of the observed mean monsoon precipitation response to anthropogenic forcing based on the CMIP6 experiments. Note the contrasting response in the GHG-only (GHG) and Aerosol-only (AER) experiments relative to Historial-Natural (HistNAT). *(b)* Box-whisker plots of the future projected changes (%) in monsoon rainfall for near-term (2020-2040), mid-term (2040-2060) and far-future (2080-2100), based on the CMIP6 SSP2-4.5 and SSP5-8.5 scenarios (based on 24 CMIP6 models: ACCESS-CM2, ACCESS-ESM1-5, AWI-CM-1-1-MR, BCC-CSM2-MR, CanESM5, CESM2, CESM2-WACCM, CIESM, CMCC-CM2-SR5, EC-Earth3, FGOALS-f3-L, FGOALS-g3, GFDL-ESM4, IITM-ESM, INM-CM4-8, INM-CM5-0, IPSL-CM6A-LR, KACE-1-0-G, MIROC6, MPI-ESM1-2-HR, MPI-ESM1-2-LR, MRI-ESM2-0, NESM3, NorESM2-LM). The future projected changes are relative to the present-day (1951-2014). Note that the SSP5-8.5 projection shows higher percentage change as compared to SSP2-4.5, with large variability especially for the far-future.

2.1 Observed changes

Paleoclimate proxy records provide evidence for long-term variations in the Asian / Indian monsoon arising from solar insolation changes caused by Sun-Earth orbital forcing (e.g., Caley et al., 2011). The influence of precessional forcing on the intensification of the West African monsoon during the mid-Holocene, a period about 6000 years BP with maximum summer solar insolation over the Northern Hemisphere (NH), is well-documented both in observational and modeling studies (eg., Braconnot et al., 2019; Weldeab et al. 2007). While the declining trend of the orbitally-forced NH solar insolation since mid-Holocene provides an important climatic constraint (e.g., Caley et al., 2011), robust detection of long-term weakening of the South Asian monsoon rainfall remains challenging, in part due to the strong monsoon internal variability on multi-decadal time-scales (e.g., Sinha et al., 2015; Prasad et al., 2014) and also due to the differences in monsoonal changes estimated from widely different proxy records (e.g., Flietmann et al., 2003; Gupta et al., 2005; Sarkar et al., 2000). However, recent studies seem to indicate a more conclusive role of precessional forcing on a long-term weakening of the Indian monsoon since the mid-Holocene as inferred from proxy-based evidences (e.g., Nagoji and Tiwari, 2017) and long transient climate model simulations (e.g., Bracconot et al., 2019).

Rainfall observations from the India Meteorological Department (IMD), available since 1871, reveal significant interannual and decadal time-scale variations in the Indian summer monsoon rainfall (ISMR), which are linked to patterns of sea surface temperature (SST) variations in the tropical Pacific Ocean associated with the El Niño/Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO); as well as in the tropical Indian Ocean (see Turner and Annamalai, 2012; Kulkarni et al., 2020 and references therein). An additional noteworthy aspect is the moderate declining trend of the Indian summer monsoon rainfall since the latter half of the 20th century, characterized by prominent decrease of precipitation over parts of north-central, west coast and north-east India (e.g., Guhathakurta and Rajeevan, 2008; Krishnan et al., 2016; Roxy et al., 2015; Guhathakurta et al., 2015; Kulkarni et al., 2020). This feature is consistently supported by a weakening trend of the large-scale monsoon circulation during this period (Krishnan et al., 2013; Abish et al., 2013). Some studies have attributed this recent weakening of the South Asian monsoon to the influence of NH anthropogenic aerosol forcing which has offset the expected intensification of monsoon precipitation due to greenhouse gas (GHG) forcing (e.g., Bollasina et al., 2011; Polson et al., 2014; Krishnan et al., 2016; Undorf et al., 2018). Results from the CMIP6 experiments also lend support to the role of anthropogenic aerosol forcing on the observed declining trend of the South Asian monsoon precipitation during 1951-2014 (Fig.1a). Besides anthropogenic aerosols, the effects due to the rapid warming of the equatorial Indian Ocean SST during the last few decades (see Swapna et al., 2014; Roxy et al., 2015), together with decadal time-scale internal variations of the tropical climate system (Wang et al., 2020; Salzmann and Cherian, 2015; Huang et al., 2020) also appear to have influenced the monsoonal weakening in the recent few decades.

On the other hand, there is robust evidence which shows that the frequency of occurrence of localized very heavy rainfall events (intensity > 150 mm day^{-1}) during the summer monsoon season has significantly risen over Central India during the past 6-7 decades, at the expense of low and moderate rain events, which is in part related to increase of atmospheric moisture content in a warming environment (i.e., Clausius-Clapeyron relation) and partly due to increased variability of moisture transported from the Indian Ocean (e.g., Goswami et al., 2006; Rajeevan et al., 2008; Roxy et al., 2017).

2.2 Future projections

With continued global warming and possible reductions in NH aerosol emissions, future changes in the monsoon precipitation are expected to be prominently constrained by the effects of increasing surface temperature and atmospheric moisture. Projections from the CMIP5 models generally indicate an increase in the mean, extremes and variability of the South Asian monsoon precipitation towards the end of the 21st century, with considerable spread across models (e.g., Kitoh et al., 2013; Krishnan et al., 2020; Kulkarni et al., 2020). The projected increase of monsoon precipitation during the 21st century is also seen in the CMIP6 models (Fig.1b).

Here it must also be mentioned that the near-term (2020-2040) future projections of monsoon precipitation are subject to several uncertainties, such as decadal changes in the internal modes of variability, uncertainties in model representation of physical processes, future anthropogenic aerosol emissions, stratospheric aerosols from future volcanic eruptions, etc., (e.g., Huang et al., 2020; Wang et al., 2020).

3. Concluding remarks:

In summary, there is *high confidence* that the projected mean and variability of the South Asian monsoon precipitation will increase in the future, particularly in the latter half of the 21st century due to continuation of global warming. There is a major need, however, to improve the representation of key physical processes in the next generation of climate models and address knowledge gaps pertaining to regional monsoons.

While the coupling of monsoon precipitation and large-scale circulation is central in the context of the present-day climate (Sabin et al., 2013), it is not clear how the monsoon precipitation-wind coupling would behave in an increasingly warming world. The answer to this question has important regional implications (Krishnan et al., 2020). The CMIP future projections suggest a likely weakening of monsoon winds and large-sale meridional overturning circulation, despite increase of monsoon precipitation under global warming (Kitoh et al., 2013; Krishnan et al., 2013). In fact, many CMIP5 models show a decoupling of monsoon winds and precipitation even for the historical 20th century simulations (Saha et al., 2014). An exception to this paradoxical behavior of monsoon wind and precipitation response to GHG-forcing is seen in the high-resolution (grid size < 35 km) global simulation with telescopic zooming over South Asia (Krishnan et al., 2016; see Fig.2). It is important to note the monsoon

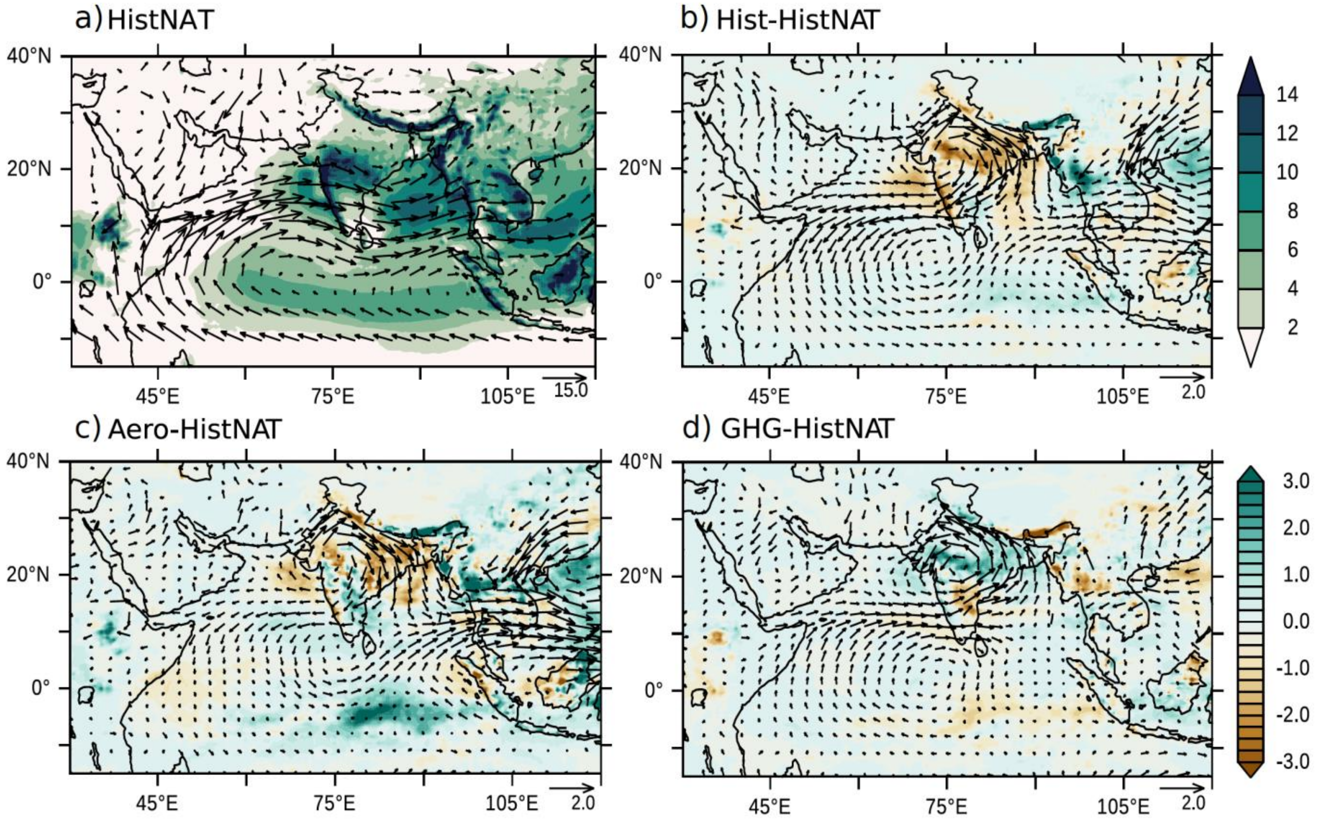

Fig.2: Anthropogenic influence on the South Asian monsoon: GHG and Aerosol forcing: *(a)* Spatial map of JJAS mean rainfall (mm day^{-1}) and 850 hPa winds (ms^{-1}) from the HistNAT simulation for the period (1951-2005) based on a global climate model with high-resolution (grid size < 35 km) telescopic zooming over South Asia (see Krishnan et al. 2016). Also shown are the difference maps of the JJAS mean rainfall and winds for the Historical all-forcing (Hist), Aerosol-only (AER) and GHG-only (GHG) experiments relative to HistNAT *(b)* [Hist - HistNAT] *(c)* [AER-HistNAT] *(c)* [GHG-HistNAT]. It is important to highlight the strengthening of the large-scale monsoon circulation in the GHG experiment, together with enhancement of precipitation over India. Both the Hist and AER experiments show distinct weakening of monsoon precipitation and circulation, relative to HistNAT. Note that the AER experiment is a new addition to the high-resolution simulations, since the earlier study by Krishnan et al. (2016).

low-level southwesterly winds are intensified alongside an increase of precipitation over the Indian region, in the GHG-only forcing experiment (Fig.2d). On the other hand, the aerosol-only forcing (AER) and all-forcing (Hist) experiments show weakening of the monsoon precipitation and circulation response, relative to the HistNAT experiment (Figs.2b-c).

Thermodynamic arguments suggest that the projected weakening of tropical circulation in response to global warming is related to a faster rate of increase of atmospheric moisture, as compared to precipitation, which leads to increased dry static stability of the atmosphere and weakens the tropical large-scale circulation e.g., Pacific Walker circulation (Held and Soden, 2006). Applying this argument to the South Asian monsoon is not straightforward, especially given that the CMIP models produce excessive convective precipitation over the monsoon region with large biases in the distribution of stratiform and convective precipitation types (Sabeerali et al., 2015). Biases in simulating the precipitation-types are known to introduce large errors in the monsoon latent heating, temperature and circulation fields (Krishnamurti et al., 2010). Improving the representation of stratiform and convective precipitation in climate models is essential to ensure proper coupling between the monsoon precipitation and large-scale circulation (Choudhury and Krishnan, 2011).

Additionally, the CMIP class of models reveal large negative biases in simulating the mean monsoon precipitation over South Asia (e.g., Sperber et al., 2013). Reducing the dry bias in monsoon precipitation entails realistic representation of key physical processes that are observed over the South Asian monsoon environment viz., warm rain processes, orographic precipitation, large-scale organized stratiform precipitating systems, vertical structure of latent heating, low-level clouds, cloud-aerosol feedbacks, land-atmosphere coupling etc., (e.g., Houze, 1997; Romatschke and Houze, 2011; Konwar et al., 2014; Shige et al., 2017; Utsav et al., 2017; Barton et al., 2019).

In addition, there is also an urgent necessity to improve climate models to realistically capture the large-scale tropical atmosphere-ocean coupled interactions, modes of internal climate variability and their teleconnections to the South Asian monsoon precipitation (Annamalai et al. 2017). Most importantly, it is acknowledged that improving the regional monsoon precipitation in weather and climate models is a seamless process across scales and warrants systematic evaluation of simulations, refinement of parameterization schemes and data assimilation techniques (Bauer et al., 2015), and application of innovative methodologies such as artificial intelligence and machine learning for advancing predictive capabilities (Reichstein et al., 2019).

References:

Abish, B., Joseph, P.V. and Johannessen, O.M., 2013: Weakening trend of the tropical easterly jet stream of the boreal summer monsoon season 1950-2009. *J. Clim.*, 26:9408-9414.

Annamalai, H., Taguchi, B. and McCreary, J.P., 2018: Systematic errors in South Asian monsoon simulation: Importance of equatorial Indian Ocean processes. *J. Clim.*, 30 (20): 8159-8178.

Barton, E.J. et al., 2019: A case-study of land-atmosphere coupling during monsoon onset in northern India. *Q. J. R. Meteorol.Soc.*, 1-15.

Bauer, P., Thorpe, A. and Brunet, G., 2015: The quiet revolution of numerical weather prediction. *Nature*, 525, 47-55. doi:10.1038/nature14956

Bookhagen B. and Burbank, D.W., 2010: Toward a complete Himalayan hydrological budget: spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *J. Geophys Res.*, 115:F03019.

Bollasina, M.A., Ming, Y. and Ramaswamy, V., 2011: Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *Science*, 334, 502-505.

Braconnot, P. et al., 2019: Impact of multiscale variability on last 6,000 Years Indian and West African monsoon rain. *Geophys. Res. Lett.*, 46, 14,021-14,029.

Caley, T. et al., 2011: New Arabian Sea records help decipher orbital timing of Indo-Asian monsoon. *Earth Planet. Sci. Lett.* 308:433-44.

Choudhury, A.D. and Krishnan, R., 2011: Dynamical response of the South Asian Monsoon trough to latent heating from stratiform and convective precipitation. *J. Atmos. Sci.*, 68(6):1347-1363.

Fein, J.S., and Stephens, P.L., 1987: Monsons. John Wiley, New York.

Fleitmann, D. et al., 2003: Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman, *Science*, 300, 1737-1739.

Gadgil, S., 2003: The Indian monsoon and its variability. *Annu. Rev. Earth Planet. Sci.*, 31, 429-467.

Goswami, B.N. et al., 2006: Increasing trend of extreme rain events over India in a warming environment. *Science*, 314 (5804):1442-1445.

Guhathakurta, P. and Rajeevan, M., 2008: Trends in rainfall patterns over India. *Int. J. Climatol.*, 28:1453-1469.

Guhathakurta, P. et al., 2015: Observed changes in southwest monsoon rainfall over India during 1901-2011. *Int. J. Climatol.,* 35(8):1881-1898.

Gupta, A.K., Das, M. and Anderson, D.M., 2005: Solar influence on the Indian summer monsoon during the Holocene, *Geophys. Res. Lett.*, 32, L17703, https://doi.org/10.1029/2005GL022685.

Held, I.M. and Soden, B.J., 2006: Robust responses of the hydrological cycle to global warming. *J. Clim.,* 19: 5686-5699.

Houze, R.A., 1997: Stratiform precipitation in regions of convection: a meteorological paradox? *Bull. Am. Meteorol. Soc.*, 78 (10), 2179-2196.

Huang, X. et al., 2020: South Asian summer monsoon projections constrained by the Interdecadal Pacific Oscillation. *Sci. Adv.*, 6 (11), eaay6546.

IPCC, 2013: Climate Change: The physical science basis. Contribution of working group I to the Fifth assessment report of the intergovernmental panel on climate change (Stocker, T.F. et al. (eds)). Cambridge University Press, Cambridge.

Keshavamurty, R.N. and Sankar Rao, M., 1992: The Physics of Monsoons. Allied Publishers Ltd, Bombay.

Kitoh, A. et al., 2013: Monsoons in a changing world: a regional perspective in a global context. *J. Geophys. Res.*, 118, 3053-3065, https://doi.org/10.1002/jgrd.50258.

Konwar, M. et al., 2014: Microphysics of clouds and rain over the Western Ghat. *J. Geophys. Res. Atmos.*, 119(10):6140-6159.

Krishnamurti, T.N. and Surgi, N., 1987: Observational aspects of the summer monsoon. In: *Monsoon Meteorology*, C.-P. Chang and T.N. Krishnamurti, Eds., Oxford University Press, 3-25.

Krishnamurti, T.N., Chakraborty, A. and Mishra, A., 2010: Improving multimodel forecasts of the vertical distribution of heating using the TRMM profiles. *J. Clim.*, 23, 1079-1094.

Krishnan, R. et al., 2013: Will the South Asian monsoon overturning circulation stabilize any further? *Clim. Dyn.*, 40, 187-211.

Krishnan, R. et al., 2016: Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. *Clim. Dyn.*, 47, 1007-1027.

Krishnan, R. et al., 2020: Introduction to climate change over the Indian region. In: *Assessment of Climate Change over the Indian Region,* R. Krishnan et al. (Eds), Springer Nature, Springer, Singapore, pp 1-46.

Kulkarni, A. et al., 2020: In: *Precipitation changes in India.* In: *Assessment of Climate Change over the Indian Region,* R. Krishnan et al. (Eds), Springer Nature, Springer, Singapore, pp 47-72.

Nagoji, S.S. and Tiwari, M., 2017): Organic carbon preservation in Southeastern Arabian Sea sediments since mid-Holocene: Implications to South Asian Summer Monsoon variability, *Geochem. Geophys. Geosyst.*, 18, https://doi.org/10.1002/2017GC006804.

Polson, D. et al., 2014: Decreased monsoon precipitation in the Northern Hemisphere due to anthropogenic aerosols. *Geophys. Res. Lett.* 41, 6023-6029. https://doi.org/10.1002/2014GL060811.

Prasad, S. et al., 2014: Prolonged monsoon droughts and links to Indo-Pacific warm pool: A Holocene record from Lonar Lake, Central India. *Earth Planet. Sci. Lett.,* 391, 171-182.

Rajeevan, M.N., Bhate J. and Jaswal, A.K., 2008: Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophys. Res. Lett.*, 35:L18707.

Rajeevan, M.N. and Nayak, S. (Eds), 2017: *Observed Climate Variability and Change over the Indian Region.* Springer Geology, Springer, Singapore.

Reichstein, M. et al., 2019: Deep learning and process understanding for data-driven Earth system science. *Nature*, 566, 195-204. https://doi.org/10.1038/s41586-019-0912-1.

Romatschke, U. and Houze, R.A., Jr., 2011: Characteristics of precipitating convective systems in the South Asian monsoon. *J. Hydrometeor.*, 12, 3-26.

Roxy, M.K. et al., 2015: Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. *Nat. Commun.*, 6: 7423, https://doi.org/10.1038/ncomms8423.

Roxy, M.K. et al., 2017: A threefold rise in widespread extreme rain events over central India. Nat. Commun., 8:708.

Sabeerali, C.T. et al., 2015: Why ensemble mean projection of South Asian monsoon rainfall by CMIP5 models is not reliable? *Clim. Dyn*., 45(1-2):161-174.

Sabin, T.P., 2013: High resolution simulation of the South Asian monsoon using a variable resolution global climate model. *Clim. Dyn.*, 41 (1):173-194.

Saha, A. et al., 2014: Failure of CMIP5 climate models in simulating post-1950 decreasing trend of Indian monsoon, *Geophys. Res. Lett.*, 41, 7323-7330, doi:10.1002/2014GL061573.

Salzmann, M. and Cherian, R., 2015: On the enhancement of the Indian summer monsoon drying by Pacific multidecadal variability during the latter half of the twentieth century. *J. Geophys. Res. Atmos.* 120(18), 9103-9118.

Sarkar, A. et al., 2000: High-resolution Holocene monsoon record from the eastern Arabian Sea, *Earth Planet. Sci. Lett.,* 177, 209-218.

Schneider, T., Bischoff, T. and Haug, G.H., 2014: Migrations and dynamics of the intertropical convergence zone. *Nature*, 513, 45-53, https://doi.org/10.1038/nature13636.

Shige, S., Nakano, Y. and Yamamoto, M.K., 2017: Role of orography, diurnal cycle, and intraseasonal oscillation in summer monsoon rainfall over Western Ghats and Myanmar coast. *J. Climate*, 30, 9365-9381.

Sinha, A. et al., 2015: Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia. *Nat. Commun.* 6, 1-8. https://doi.org/10.1038/ncomms7309.

Sperber, K.R. et al., 2013: The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century. *Clim. Dyn.*, 41:2711-2744.

Swapna, P., Krishnan, R. and Wallace, J.M., 2014: Indian Ocean and monsoon coupled interactions in a warming environment. *Clim. Dyn.*, 42 (9-10), 2439-2454.

Turner, A.G. and Annamalai, H., 2012: Climate change and the South Asian summer monsoon. *Nature Climate Change*, 1-9, https://doi.org/10.1038/NCLIMATE1495.

Undorf, S. et al., 2018: Detectable Impact of Local and Remote Anthropogenic Aerosols on the 20th Century Changes of West African and South Asian Monsoon Precipitation. *J. Geophys. Res. (Atmos.),* 123, 4871-4889. https://doi.org/10.1029/2017JD027711.

Utsav, B. et al., 2017: Statistical characteristics of convective clouds over the Western Ghats derived from weather radar observations. *J. Geophys. Res. Atmos.*, 122, 10 050-10 076.

Wang, B. et al., 2020: Monsoon climate change assessment. *Bull. Am. Meteorol. Soc*., https://doi.org/10.1175/BAMS-D-19-0335.1.

Webster, P.J. et al., 1998: Monsoons: processes, predictability, and the prospects for prediction. *J. Geophys. Res.*, 103:14,451-14,510.

Weldeab, S. et al., 2007: 155000 years of West African monsoon and ocean thermal evolution, *Science*, 316, 1303-1307.

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