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A kaleidoscopic research memoir on Indian summer monsoon rainfall

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सार – भारतीय ग्रीष्मकालीन मॉनसून वर्षा (ISMR) के संचालन तंत्र और बदलती हुई जलवायविक परिस्थियों में इसके भविष्य को समझना अत्यंत महत्वपूर्ण है। एक मजबूत नीति निर्माण के लिए भारतीय ग्रीष्मकालीन मॉनसून वर्षा एक प्रमुख इनपुट है, जिसके बिना कृषि आधारित भारतीय अर्थव्यवस्था एवं घनी आबादी वाले क्षेत्रों को भारी हरजाना भरना पड़ सकता है। तथापि भारतीय ग्रीष्मकालीन मॉनसून वर्षा सबसे जटिल घटनाओं में से एक है जिसमें भिन्न-भिन्न परिस्थितियाँ शामिल होती हैं। ISMR की जटिलता का कारण इसे प्रभावित करने वाले बाह्य कारकों में स्थानिक-कालिक परिवर्तिता होती हैं। इन कारकों में वैश्विक परिस्थितियाँ शामिल होती हैं जैसे कि विभिन्न टेलीकनेक्शन और क्षेत्रीय परिस्थितियाँ जिसमें भूमि के उपयोग में परिवर्तन और भू-स्तर पर होने वाली प्रतिपुष्टि प्रक्रियाएँ शामिल हैं। इन सभी बाधाओं के बावजूद, भारतीय ग्रीष्मकालीन मॉनसून वर्षा के विभिन्न पहलुओं को समझना और बदलती जलवायविक परिस्थितियों में संभावित परिवर्तनों को दूर करना सबसे महत्वपूर्ण है। जहाँ हम भारतीय ग्रीष्मकालीन मॉनसून वर्षा से संबंधित अलग-अलग शोध समस्याओं पर एक संक्षिप्त समीक्षा प्रस्तुत करने के लिए ISMR पर चर्चा आरंभ करते हैं और मौजूदा शोध अंतराल की ओर ध्यान आकर्षित करने के लिए कुछ महत्वपूर्ण निष्कर्षों को संक्षेप में प्रस्तुत कर रहे हैं। ISMR पर इस संस्मरण को प्रस्तुत करने के पीछे मुख्य ध्येय पाठकों को एक समग्र स्थिति स्पष्ट कराना है जो इस दिशा में आगे के शोध कार्य का आधार बनेगा।

ABSTRACT. Comprehending the governing mechanism of Indian summer monsoon rainfall (ISMR) and its fate under changing climatic conditions is extremely important. ISMR is the key input required for robust policy formulations, without which the agriculture-based Indian economy and high population density regions may face severe reparations. However, ISMR is one of the most complex phenomena involving different forcings. The complexity of ISMR lies in the spatio-temporal variability of the external factors influencing it. These factors involve global forcings such as different teleconnections and regional forcings such as land-use change and land-surface feedback processes. Despite all odds, understanding different aspects of ISMR and foresee the possible alterations under changing climatic conditions are of paramount importance. Here, we initiate a discussion on ISMR to provide a brief review of different research problems pertaining to ISMR and summarize a few important findings to draw attentions towards existing research gaps. The premise behind this memoir on ISMR is to provide the readers with an overall picture that will form bedrock for the further research.

Key words – ISMR, Variability, Downscaling.

1. Introduction

Indian Summer Monsoon Rainfall (ISMR), the major contributor of the South Asian Monsoon, is an important factor controlling water resources, agriculture and ecosystems throughout India. Agriculture, the backbone of Indian economy, is still heavily dependent on ISMR. Hence, it is necessary to understand and predict/project the fate of this climate variable to aid better planning. Such a phenomenon of extreme importance, however, is a classic example of colossal complexity. If viewed through the glasses of science, ISMR is a result of combinations of a lot of different systems interacting with each other. Hence, predicting rainfall at any location demands the study of monsoon dynamics at synoptic scale in conjunction with regional drivers affecting the monsoon at that location.

Fig. 1 shows the pictorial representation of global and regional drivers affecting rainfall in general. The initial perception about ISMR was a gigantic land-sea breeze driven by the land-ocean surface temperature contrast. Gadgil (2018) actually established that this definition of monsoon is not supported by the observations. On the other hand, considering the monsoon as a manifestation of seasonal movement of intertropical convergence zone (ITCZ) is consistent with the observation and hence, it is more appropriate definition. ISMR is characterized by the variability at different temporal (such as intra-seasonal, inter-annual etc.) and spatial scales. Monsoon onset, which indicates arrival of monsoon over India and has shown a delayed behavior in the recent decades (Sahana *et al*., 2015) represents a part of inter-annual variability. Intra-seasonal variability is

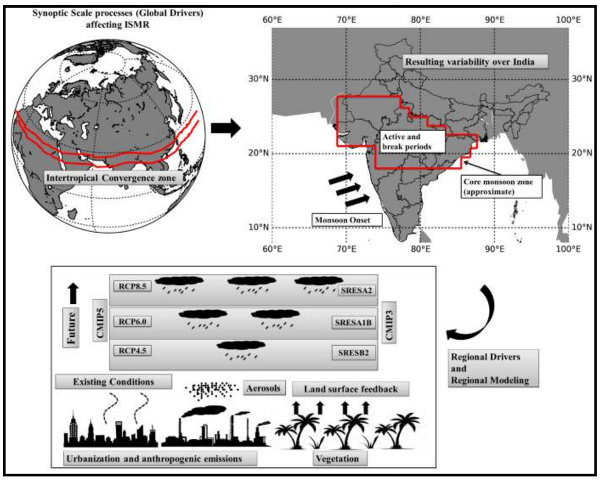

Fig. 1. Pictorial representation of the global and local forcings affecting ISMR and future projections scenarios
[At synoptic scales, the ISMR (seasonal shift of intertropical convergence zone shown by red lines) is affected by complex interaction of atmospheric component (e.g., westerlies in tropics) and oceanic component (e.g., El Nino-Southern oscillation) resulting in intra-seasonal (active-break phases over core monsoon zone shown by red lines over India) and inter-annual (monsoon onset) variabilities. At regional level, the local forcings such as urbanization, anthropogenic emissions, land-surface feedbacks, aerosols etc. govern the rainfall. For impacts assessment, the coarse resolution climate variables provided by GCMs pertaining to different CMIP3 (SRESA2, SRESA1B, SRESB2) and CMIP5 (RCP4.5, RCP6.0, RCP8.5) scenarios are downscaled to get future rainfall projections at fine resolution]

revealed by the presence of active and break phases of monsoon (Rajeevan *et al*., 2010) over the core monsoon zone as shown in Fig. 1. This temporal variability is required to be understood to gauge the *overall* consequences of monsoon over India.

The spatial variability of ISMR is mainly governed by the local drivers. These involve orography, land-use change in terms of urbanization, land-surface feedback processes brining in the terrestrial moisture sources into the picture, anthropogenic emissions, aerosols (Patil *et al*., 2018) etc. These regional forcings shape the spatial pattern of rainfall. Thorough understanding of both global and local drivers is extremely important to comment about the rainfall at a particular location and its possible variations in future. Future projections of the climate variables are provided by the General Circulation Models (GCMs). GCMs are expected to understand the forcings at both levels for skillful projections. However, on account of the spatial resolution at which they work, important subgrid features are missed, which affect the skills of GCMs in capturing important features of ISMR. Also, the coarse resolution of GCMs acts as an impediment in utilizing the data for impacts assessment. In order to address this problem, the downscaling techniques are incorporated. There are two types of downscaling techniques *viz*., (*i*) dynamical and (*ii*) statistical. Dynamical downscaling (DD) (Devanand *et al*., 2018) models are basically regional climate models at fine resolution, whereas statistical downscaling (SD) (Kannan and Ghosh, 2013; Salvi *et al*., 2013) models are data driven approaches used for rainfall projections. The projections are obtained for the climate scenarios prescribed by Intergovenmental Panel on Climate Change (IPCC). The scenarios are basically the initial or boundary conditions that are used by GCMs as inputs for obtaining future projections. Different scenarios are clubbed under the heading Coupled Model Intercomparison Project (CMIP). CMIP3 and CMIP5 are the third and the fifth phases of the project respectively. All the GCMs provide the rainfall projections for these scenarios and it is expected to use as many GCMs as possible for the analysis to have more confidence in the projections. However, usage of multiple GCMs introduces uncertainty in the projections, which are required to be modelled to get a clear picture about the skills.

In this review paper, we provide a brief description about the research work carried out over ISMR from different perspective. The research domains mainly involve rainfall projection (section 2), uncertainty modelling (section 3), Inter-annual variability: Onset (section 4), intra-seasonal variability (section 5), land-surface feedbacks (section 6) and urbanization and rainfall extremes (section 7). We end the manuscript with Summary and concluding remarks.

2. Rainfall projections

GCMs have provided the scientific community with the plausible fate of different climate variables for different scenarios (CMIP5 suite of experiments). For sure, these data portray an overall picture about trajectories of climate variables; however, the spatial resolution at which the data is available is coarse. For impacts assessment, the data is required at much finer resolution. The downscaling techniques (DD, SD) help us to get the data at finer resolution. SD techniques are data driven models, which leverage the established relationship between climate variables at coarse resolution (called predictors) and fine resolution climate variable of interest e.g., rainfall (called predictand) over historic period to produce future projections. Ghosh and Mujumdar (2005) and Ghosh and Mujumdar (2008) used fuzzy clustering technique and Relevance Vector Machine (RVM) respectively as downscaling methodologies. Former study used the technique to forecast monthly rainfall over Orissa; whereas the later study used the methodology to model the streamflow for Mahanadi river basin.

Kannan and Ghosh (2013) proposed a SD methodology, which was a combination of weather typing and transfer function based approaches. This multisite statistical downscaling technique actually outperformed different other contemporary methodologies then, especially in capturing properties of observed data such as cross correlation. This methodology was successfully demonstrated over the Mahanadi river basin. Salvi *et al.* (2013) used this methodology and carried out statistical downscaling over India. This was the first attempt then to obtain the data at 0.5° resolution over entire India for historic period and future. (*i*) lack of visually significant trend in ISMR (for future) and (*ii*) intensification of changes in mean rainfall (with respect to historic mean) keeping spatial pattern the same are two important outcomes of this study. As discussed before, for the impacts assessment, fine resolution data is required. However, it is necessary to check if there is any real value addition by going finer. Shashikanth *et al.* (2014) undertook this research problem and carried out SD at three different spatial resolution *viz*., 0.05°, 0.5° and 0.25°. The results showed that mere increase in resolution by a way of computationally more expensive SD does not necessarily contribute towards improving the signal strength. Shashtri *et al*. (2017) and Shashikanth *et al.* (2017) applied SD methodologies for getting forecasts and projections of extreme rainfall respectively and acquired reasonable skills in capturing extremes.

One of the limitations of SD models is that the resolution at which the data can be downscaled is limited by the resolution of the observed data. On the other hand DD models are known for obtaining the data at much finer resolution. Singh *et al*. (2016) used dynamically downscaled data product known as Coordinated Regional Climate Downscaling Experiment (CORDEX) and evaluated the skills over India. The skills are found to be mediocre as compared to the parent GCM. Devanand *et al*. (2018) established that if there is proper understanding of the model sensitivities to physics and resolution and its effect on the model uncertainties, the DD model works better. This was illustrated with Weather Research and Forecasting (WRF) model applied over India. It was also found that spectral nudging helps in reducing uncertainty.

3. Uncertainty modeling

Dealing with multiple GCMs, diverse scenarios, a plethora of downscaling techniques, set of reanalysis data and different hydrologic models result in uncertainties. Quantification and modelling of such uncertainties is extremely important as it is the symbol of consensus among different data and approaches. We tend to build more confidence in the models revealing less uncertainty. Such analyses were carried out in past at different spatial scales right from river basin level over to entire Indian land mass.

Mujumdar and Ghosh (2008) focused on modelling GCM and scenario uncertainty using weights in computing the probabilistic mean of the cumulative distribution functions (CDFs). Ghosh and Mujumdar (2009) modelled inter-model uncertainty with an approach known as imprecise probability, where the probability is represented as an interval gray number. This approach is advantageous as compared to previous one. This is mainly because (*i*) the CDF generated with one GCM is different from that with another and representing this band of CDFs with a single valued weighted mean CDF may be misleading and (*ii*) Imprecise CDF represents an envelope, which contains the CDFs generated with all the available and the missing GCM output. Kannan *et al*. (2014) modelled the uncertainty originating from observed gridded rainfall products and reanalysis data. The study was carried out over entire Indian landmass. It also established the prime cause behind differences in the spatial patterns of rainfall, obtained with reanalysis data and GCM using partial correlation analysis. Sharma *et al.* (2018) evaluated the uncertainty emanating from different downscaling techniques. However, the study concluded that this uncertainty is significantly less in magnitude as compared to the inter GCM uncertainty. Joseph *et al.* (2018) assessed uncertainty in the parameters of hydrologic model by generating 1000 sets using Monte Carlo simulation technique and running the hydrologic model over the Ganga river basin. The results are in consent with the study by Sharma *et al.* (2018). Uncertainty resulting from the multiple parameters is less as compared to the GCM uncertainty.

4. Inter-annual variability: Monsoon onset

Onset of the ISMR (onset here onwards), which represents the beginning of the South Asian monsoon holds the key to solve some important questions. It not only detects the properties of the monsoon but also plays an important role in controlling the crop calendar and agricultural domain. Unfortunately, such an important parameter reveals substantial inter-annual variability, which has corresponding reparations over the agricultural produce. Here, we would like to steer the attention of the readers to two studies, which successfully attempted answering important questions about the onset *viz*., (*i*) is there any change in the onset as compared to the past and (*ii*) can we predict the onset with some credibility? Sahana *et al*. (2015) used Hydrologic Onset and Withdrawal Index over the Arabian Sea for calculating onset dates and explained a chain of events such as (*i*) regime shift in the tropical Pacific sea surface temperature during 1976-77; (*ii*) a delay in the development of easterly vertical shear during May-June resulting in the reduction of moisture supply from the Indian Ocean and (*iii*) reduced moisture availability over the Arabian Sea because of enhanced precipitation over the Indian Ocean. Having understood the probable reasons affecting onset, Sahana and Ghosh (2018) proposed integrated statistical dynamical model for its prediction. The model illustrated improved correlation of 0.6 between simulated and observed onset dates with the proposed integrated statistical dynamical model as compared to 0.44 obtained with the operational dynamic monsoon prediction model. Considering the complexities associated with the challenging task such as onset prediction, the achieved skills in the predictions are fair.

5. Intra-seasonal variability: Active and break phases

Intra-seasonal variability of ISMR is usually represented in terms of active and break periods. These periods are characterized by the enhanced OR suppressed activity of ISMR. Rajeevan *et al*. (2010) established the definitions of these events as the periods in the months of July and August (peak monsoon activity), in which the normalized anomaly of the rainfall over the core monsoon zone exceeds +1 (active) or less than -1 (break) for three consecutive days. Pathak *et al*. (2017) studied these events and found out two sources *viz*., the Indian Ocean (which contributes to Indian landmass) and Ganga basin (which contributes to the core monsoon zone). Formation of monsoon trough over Indo-Gangetic plain brings moisture from the Bay of Bengal and Ganga basin to the core monsoon zone in addition to the southwesterly jets from the Indian Ocean. This shows that there is a need to consider terrestrial sources of moisture along with oceanic sources.

6. Land-surface feedbacks

Usually rainfall is condensation of the moisture present in air and it is complex process. The moisture gets transported with the wind and gets precipitated depending on other conditions. Understanding the source of moisture could help in possible variations that are observed. The largest sources of moisture are the oceans and ISMR is no exception. However, the process of evapotranspiration (EVT), which is an ongoing process, adds a twist to the proposition that the water bodies are the major sources of moisture. Enhanced EVT trigger land surface feedback mechanics, which results in elevated moisture level, which might contribute to the rainfall.

Pathak *et al*. (2014) carried out an interesting study, where the amount of EVT resulting in precipitation recycling over the Indian subcontinent is investigated. Precipitation recycling is a process (part of hydrologic cycle), which implies that the moisture evaporated over a landmass results in the precipitation over the same landmass. The study reported a few interesting facts such as enhanced soil moisture and EVT, especially in vegetative areas contribute to 25 per cent of recycling ratio especially in the month of September. This is predominantly seen in the northeast region of India, where the green land cover prevails. However, the study spells out a possibility of delayed withdrawal of monsoon because of recycling and also alarms about rapidly decreasing trend of recycled precipitation in the northeastern part of India.

Another study by Paul *et al*. (2018) reveals that the water-deficit state of Tamil Nadu receives 25-40% of the rainfall from the moisture, emanating from the EVT through the dense vegetation cover of the Western Ghats. Of course, this cannot be categorized as precipitation recycling. However, it is noteworthy that the source of moisture is again landmass, where EVT plays the key role. This contribution goes up to 50% during monsoon-deficit years, which looks to be a natural recuperating mechanism. Both the studies scream out the importance of vegetation in imitating land surface feedback mechanisms, which provide an aid mainly in water deficit phases.

7. Urbanization and rainfall extremes

Extreme rainfall events are catastrophic in nature and usually leave indelible marks over the affected region. 26th July, 2005 rainfall event over Mumbai (India) was one such event, which is still remembered for all negative reasons. While, many scientists are working on rainfall projections for future, a special treatment is required to be given to understand and predict such event well in advance to provide authorities with time to develop and implement management plan. Although it is established that the synoptic scale forcings govern overall circulation resulting in ISMR over a large spatial extent, the local parameters also play their part to alter the spatial variability of this impact relevant climate variable. We have discussed the role of such local factor in the section 6, where we describe land surface feedback mechanisms. However, it has been found that one of the regional drivers *viz*., urbanization actually affects the most destructive form of ISMR, *i.e*., extremes. Hence, in this section, we discuss about fate of rainfall extremes over India and their nexus with the land-use change.

Two important studies by Ghosh *et al*. (2012) and Roxy *et al*. (2017) brought out important findings about the past rainfall extremes. Ghosh *et al*. (2012) applied generalized extreme value theory to annual maximum rainfall over India and observed increasing spatial variability in the observed rainfall extremes rather than uniformly increasing trends in the extreme rainfall events as established before. Roxy *et al*. (2017) established that despite weakening monsoon circulation, the locally available moisture and the frequency of moisture-laden depressions from the Bay of Bengal, there is a threefold increase in widespread extreme rainfall events over central India. This ascend is attributed to an increasing variability of the low-level monsoon westerlies over the Arabian Sea, driving surges of moisture supply, leading to extreme rainfall episodes across the entire central subcontinent. While, the study by Roxy *et al*. (2017) looked at the problem of extremes from the point of view of large scale circulation, different studies focused on establishing the possible link between the extremes and urbanization.

Vittal *et al*. (2013) carried out an analysis over 104 years of extreme rainfall over India and observed (*i*) increase in the extreme rainfall characteristics post 1950 and (*ii*) diametrically opposite trends before and after 1950. Statistical change point analysis revealed 1975 as a datum after which changes were the highest for the urbanized areas. This finding was not true for non-urban areas implying the possible impacts of urbanization on extreme rainfall trends and patterns. Findings by Vittal *et al*. (2013) were re-established by Shashtri *et al*. (2014). The study involved identifying 42 urban regions and comparing their extreme rainfall characteristics with those of surrounding rural areas. The urban signatures on extreme rainfall are found to be non-uniform. The sensitivity of rainfall extremes to the urbanization was illustrated with a detailed analysis, which is carried out over Mumbai and Alibaug having similar geographical locations.

Singh *et al*. (2016) looked at the nonstationarity in the characteristics of rainfall extremes with Generalized Additive Model. A significant nonstationarity in ISMR extremes was observed in urbanizing/developing-urban areas as compared to completely urbanized or rural areas. This is an important finding, which possibly links extent of urbanization with nonstationarity.

Paul *et al*. (2018) added a new dimension to the set of studies by investigating effect of urbanization signal on station level rainfall data. The study involved high resolution dynamical downscaling using Weather Research and Forecasting Model over Mumbai and established that the urban signature on extreme precipitation will be reflected on station rainfall only when the stations are located inside the urban pockets having intensified precipitation. Shashtri *et al*. (2018) and Gussain *et al*. (2018) show that the combination of statistical and dynamic components improves the extreme rainfall projections.

8. Summary and concluding remarks

This review paper describes different aspects of research work carried out over ISMR. The intention of this endeavor is to provide the readers with a superficial picture of ISMR so as to understand current and recent developments and take on new and challenging research problems. The discussion over ISMR gyrates from unraveling physics for monsoon onset, active and break phases, land-surface feedbacks to the application of data driven approaches and uncertainties pertaining to the rainfall projections. Delayed monsoon onset, elevated frequency of extremes, increase in break periods, insufficient skills in projecting extremes, urbanization (leading to extremes) and deforestations (affecting land surface feedbacks) are clearly leading India to an alarming situation. It is necessary to understand the gravity of possible implications and plan so that the reparations are curbed to minimum.

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