MAUSAM, **70**, 3 (July 2019), 453-464

551.509 : 551.585

Weather forecasting in India: Recent developments

SANDEEP PATTNAIK

School of Earth, Ocean and Climate Sciences

Indian Institute of Technology Bhubaneswar, Khurda, Odisha – 752 050, India

e mail : spt@iitbbs.ac.in

सार – इस समीक्षित लेख का उद्देश्य पिछले एक दशक के दौरान भारत के मौसम एवं जलवायु विज्ञान पर किए गए महत्वपूर्ण अनुसंधान उपलब्धियों को संक्षेप में उपलब्ध कराना है। ये शोध कार्य मुख्य रूप से भारत के शैक्षणिक संस्थानों, अनुसंधान केंद्रों और प्रचालनात्मक एजेंसियो द्वारा किए गए हैं। इन शोध कार्यों को मुख्य रूप से छह वर्गों अर्थात् मॉनसून, सिनॉप्टिक स्केल प्रणाली, उष्ण कटिबंधीय चक्रवात, बादल एरोसोल एवं वायु गुणवत्ता, खराब मौसम प्रणाली, डेटा सेट्स और प्रेक्षण अभियान में बाँटा गया है। भारत में मौसम और जलवायु सेवाओं पर दीर्घकालीन प्रभाव को ध्यान में रखते हुए कुछ प्रमुख परिणामों पर सीमित विचार विमर्श करके सामाजिक आर्थिक अनुप्रयोगों की व्यापक श्रेणी के लिए गत्यात्मक पूर्वानुमान प्रणालियों के कौशल में सुधार पर ध्यान केंद्रित किया गया है। जिन परिणामों पर इसमें चर्चा की गई है उनके पैमाने अलग-अलग हैं जिनमें तात्कालिक अनुमान से लेकर जलवायविक पैमाने पर अलग-अलग स्थानिक कालिक विभेदनों को शामिल किया गया है। अंत में इस अनुसंधान को मील का पत्थर मानकर आगे की चुनौतियों पर जोर दिया गया है। भारत में मौसम और जलवायु विज्ञान अनुसंधान में उत्कृष्टता प्राप्त करने की गति को बनाए रखने के लिए देश के लिए तैयार रोडमैप के माध्यम से समग्र विकास के लिए कुछ बिंदुओं का सुझाव दिया गया है। इस दिशा में निरंतर प्रयास न केवल हमारे अनुसंधान और प्रचालनात्मक पूर्वानुमान क्षमताओं को बेहतर बनाने के लिए बहुमूल्य इनपुट प्रदान करेगा बल्कि हमें 21वीं शताब्दी में भारत की मौसम और जलवायु सेवाओं में लगातार आने वाली चुनौतियों को प्रभावी ढंग से हल करने में सक्षम करेगा।

ABSTRACT. This review article aims to highlight the recent research accomplishments on weather and climate sciences of India mostly during last decade in a concise manner. These research works were mainly carried out at educational institutes, research centers and operational agencies within India. The research achievements are organized into six sections namely monsoon, synoptic scale systems, tropical cyclones, cloud aerosol and air quality, severe weather systems, data sets and observation campaign. The discussions are restricted to highlighting few key results, keeping in view its long term implications on the weather and climate services in India with focus on improving the skills of dynamical forecasting systems for wide range of socioeconomic applications. Results discussed here are comprises of different spatiotemporal scales ranging from nowcasting to climate scale. Finally, the research accomplished milestones are summarized with emphasis on challenges ahead. In order to maintain the momentum of achieving higher milestones and holistic development of weather and climate science research in India, few points with achievable roadmap are suggested. Sustained effort in this direction, will not only provide valuable inputs to improve our research and operational forecasting capabilities but also enable us to effectively address continuously evolving outstanding grand challenges in weather and climate services of India in the 21st century.

Key words – Weather, Climate science, Tropical cyclones, Clouds-aerosol and air quality.

1. Introduction

India experiences highly versatile kind of weather and climate systems round the year. These systems impact a specific region based on multiple factors, therefore task of accurate forecast with adequate lead time is enormously complex and challenging. The impact of weather and climate systems directly or indirectly influence the socioeconomic conditions of the citizens in a number of different ways namely agriculture, water management, disaster mitigation, early warning system, energy. Therefore, there is a growing need in country for improvement in accuracy of weather and climate forecasts with adequate strategic lead time for better decision support system for policy and disaster risk managers. Further, it is highly emphasized in world policy making bodies such as World Meteorological Organization (WMO), that national agencies in respective countries such as India Meteorological Department (IMD) should put strong efforts to adopt new state of the art technologies to not only provide accurate information with sufficient lead time to its citizens but also upgrade continuously to meet challenges of 21st century. New developments in science and efforts to convert them into services is a huge challenge for any country including India, because transformation of innovations and new knowledge to operational framework is complex and involves multiple stack holders with different check and balance in this process. In this context, it is pertinent to highlight and discuss few major research accomplishment milestones for weather and climate sciences in India. The major research achievements discussed in this manuscript is extensive and based on the dominant weather systems impacting Indian region. Further, while synthesizing this article, it also taken into consideration about the long term implications of these research findings, to not only improve the forecasting system in the country but also bringing in new knowledge through innovative methodology to augment our understanding about complex weather and climate processes over India. This article is sub divided into highlighting the research accomplishment in six major areas, *i.e.*, monsoon, synoptic scale systems, tropical cyclones, cloud aerosol and air quality, severe weather systems, data sets and observation campaign. The final section is entitled way forward and discusses about different challenges and steps necessary to sustain our momentum of achieving higher milestones in weather and climate sciences in India.

2. **Monsoon**

The foundation for commissioning of a dynamic coupled forecasting system for Indian summer monsoon rainfall prediction at seasonal and sub-seasonal scale was led by an implementing agreement through a memorandum of understanding (MoU) between National Oceanic and Atmospheric Administration (NOAA) and Ministry of Earth Sciences (MoES) in year 2008 (NOAA and MoES MoU, 2008).This was a watershed moment and path breaking initiative by the visionary scientists and policy administrators, which has brought out a paradigm shift in addressing the issues of weather and climate research and operational activities especially enriching the Indian monsoon forecast in the country at different spatiotemporal scales. This leads to the evolution of the Indian Institute of Tropical Meteorology Earth System Model (IITM-ESM2.0), considered as one of major backbone for monsoon and climate forecasting system in the country. Further, this model is transforming through continuous up gradation and rigorous validation in terms of incorporating accurate prognostic dynamical and physical processes (sea surface temperature, aerosol, land surface, sea ice, cloud parameterization …etc.), horizontal resolution, coupling strategies with an aim towards improving its forecast skills across multiple scales, *i.e.*, short range, extended range, seasonal and climate with special emphasize on Indian summer monsoon (ISM) rainfall. It is noteworthy to mention that, one of the major challenges in monsoon rainfall forecast is to accurately replicate El-Nino Southern Oscillation (ENSO)-Monsoon teleconnection mechanism, which is being realistically simulated by the IITMESM2.0. In addition, this is for the first time that this model will be contributing to the Inter-Governmental Panel of Climate Change (IPCC) 6th phase of coupled modelling Inter-comparison project (CMIP6). There are number of high impact publications on the performance and fidelity of this model that provides deep insight to this modelling framework and its major applications towards sub-seasonal, seasonal to climate predictions for India and the world (Swapna *et al*., 2015, 2017, 2018).

The Climate Forecasting System (CFSV2.0) model (part of IITM-ESM2.0) has been extensively used for seasonal forecasting of ISM. Saha *et al*. (2014) has shown improvements in simulations of ISM as compared previous version of CFSV1. They found that spatial pattern of seasonal mean rainfall and associated wind circulations are more realistic in improved version of CFSV2 compared to CFSV1. However, they have noted an increase in cold biases in surface temperature of CFSV2. Recently, Koul *et al*. (2018) has established that using realistic ocean initial condition in CFSV2, the dominant cold bias in seasonal forecast can be reduced over ocean and this reduction leading to better tropospheric temperature gradient between land & ocean, resulting in reduction of overall dry bias in ISM rainfall. Pradhan *et al*. (2017) using CFSV2 system showed that using objective definition of ISM onset criteria, it is possible for skilful prediction of onset dates with a season advance. It was discussed that for reasonable skill prediction of onset variability, it is pertinent to not only better represent large scale processes but also the synoptic and intraseaonal features in the dynamical modelling framework. George *et al*. (2016) has revealed that forecast skills of all India summer monsoon rainfall (AISMR) in CFSV2 mainly modulated by ENSO and Monsoon teleconnection and have proven that Indian Ocean coupled dynamics do not play an important role in prediction of AISMR. However, they have concluded that this contrarian view compared to observation findings is due to inadequate representation of ocean coupled dynamics in CFSV2 model and emphasize its need for improvement.

Keeping in view the growing need of weather information in extended range scale (up to 45 days lead time) for various applications particularly with reference to agricultural procedures in the country, the extended range prediction system (ERPAS) using CFSV2 model was conceived. Abhilash *et al*. (2014) has documented about indigenously developed ERPAS system using CFSV1 model to provide a reliable forecasting tool for intra-seasonal oscillations of ISM with lead time up to 5 pentads. Joseph *et al*. (2015) has carried out experiments to know monsoon onset over Kerala (MOK) using 16th May initial conditions for 15 years from hind cast datasets and demonstrated that ERPAS modelling system able to predict MOK with reasonable accuracy when validated against IMD declared dates. Further, they have illustrated that the ERPAS system has not only avoid bogus MOK dates but also replicated the major synoptic weather features accurately for MOK. Pattnaik *et al*. (2013) has shown the impact of cumulus parameterization on the systematic errors in CFS model from an extended range forecast scale. They have demonstrated that CFSV1 model has a systematic warming (moistening) and cooling (drying) biases at the middle and upper troposphere when using Relax Arakawa Schubert (RAS) and Simplified Arakawa Schubert (SAS) cumulus parameterization schemes respectively. Further, they have concluded that RAS produced enhanced startiform rainfall associated with upper level heating and the major contribution of model total errors were arising from the systematic component of the model errors. Readers are requested to go through more number of research publications to be aware of finer technical details of ERPAS system and its usefulness in forecasting different weather systems such as heat waves, heavy rainfall events over Indian region (Joseph *et al*., 2015; Abhilash *et al*., 2014; Sahai *et al.*, 2013). After rigorous benchmark testing, the ERPAS system has been handed over to IMD for operational activities and continuously being updated for better forecast skills (Sahai and Pattanaik, 2018).

MoES-National Centre for Medium Range Weather Forecasting (NCMRWF) has implemented a high resolution unified model based global forecasting system adopted from United Kingdom Met office (UKMET). The NCMRWF Unified model (NCUM) is a step towards developing a seamless forecasting platform for multiple applications at different temporal and spatial resolutions (horizontal and vertical) through a single window modelling framework. The NCUM a coupled system model, is providing operational forecasts for wide varieties of weather and climate systems such as monsoon, tropical cyclones, dust storms and visibility. This model is also a nucleus to the NCMRWF global ensemble prediction system (NEPS) operationally running at 12 km resolution. The NCUM is modular in nature and can be adjusted from regional to global scale starting from 1.5 km to 25 km grid resolution and 50 to 85 vertical levels at different lead times up to 168 hr (Rajagopal *et al*., 2012, 2014; Sharma *et al*., 2018).

Apart from operational agencies, there are many important studies carried out by Indian researchers addressing intriguing problems related to monsoon and climate variabilities and associate mechanisms over Indian region. Anand *et al*. (2018) analysed 28 CMIP5 models in terms of biases in ISM rainfall and surface air temperature over South Asia and noted that National Centre for Atmospheric Research (NCAR) Community Earth System Model (CESM) is found to be one of best performing models. Further, it was suggested that with an increasing in resolution from 2° to 0.5°, CESM reduces its biases in terms of rainfall and surface air temperature. Pattanayak *et al*. (2018) has suggested that RegCM Version 4.3 is able to perform the ISM rainfall with much better accuracy over Indian region compared to RegCM version 4.2. This was mainly attributed to the incorporation of upgradation of measured solar irradiance instead of keeping it constant. Further, they revealed that the improvement in ISM rainfall associated with improvement in representation of moisture flux and surface net downward shortwave fluxes over India with reduction in excessive moisture over Arabian Sea and Peninsular region. Mukhopadhyay *et al*. (2010) using high resolution Weather Research and Forecasting (WRF) model demonstrated that cumulus parameterization scheme has significant impact on ISM rainfall climatology. They found that Grell-Devenyi (GD) scheme systematically overestimated the lighter rain and underestimates the moderate rainfall throughout the season. Further, it was noted that heavy rain category was systematically overestimated by the Kain-Fritsch (KF) scheme compared to other tested schemes and KF (GD) parameterization schemes has the moist (dry) biases in the spatiotemporal distribution of the monsoon rainfall over the region. The major reason attributed to these biases was the replication of vertical velocity and heating features leading to intense or weak convective instability associated with the ISM rainfall systems. Krishnan *et al*. (2000) revealed a new mechanism for initiation of monsoon breaks through an abrupt movement of anomalous Rossby waves from Bay of Bengal into northwest and central India. Further, they have proposed that two major elements which governs the transition from monsoon normal phase to break phase through segregating intense convective regimes over Indian sub-continent and equatorial Indian ocean. These two elements are rapidly northwest propagating anomalous Rossby waves from central Bay of Bengal towards northwest India and decoupling of the eastward propagating anomaly. Recently, Jain *et al*. (2018) has proposed a new mechanism suggesting mean surface to mid tropospheric wind shear driving the convection orthogonal to the lower tropospheric winds and gravity currents generated by outflow from convection initiated by the diurnal variation of land-ocean circulation dispersing south. They have emphasized that WRF model with advanced cloud microphysics parameterization is capable and essential for resolving mesoscale convective systems with squall line structure.

Though ISM is the major rain contributor over India, the large portion of rainfall over southern peninsular region is attributed to north east monsoon (NEM). Though plethora of literatures are available for ISM, there are limited studies on NEM. Rajeevan *et al*. (2012a) discussed about distinct features of diurnal variations of rainfall both over land and ocean during this monsoon season. The rainfall peaks were found during late afternoon/evening over land and early morning over the oceanic regions. Yadav (2012) has shown that the influence of ENSO has been stronger on NEM rainfall in recent decades. The paper has suggested that due to enhanced subsidence over Indonesia region causing an increase of warming of sea surface temperature facilitating an enhanced convective activity over the area leading to frequent formation of intensified tropical storms & cyclones over the north Indian oceans. These intense rain bearing storms making landfall over peninsular India during winter monsoon season are responsible for surplus rain (floods) over the region.

3. Synoptic scale systems

In this section discussions are restricted to monsoon low pressure systems and western disturbances (WD). Baisya *et al*. (2018) has showed that in a climate change regime, there is an increase in trend of lower to mid tropospheric moisture over the Indian region. Through climate surrogate experiment mechanisms they have shown that, enhanced moisture condition will facilitate making monsoon depressions stronger in coming days in terms of rainfall amount and intensity over the region. Baiysa *et al*. (2017) has also demonstrated robust influence of land surface properties especially impact of soil moisture on the characteristics of the monsoon depression with focus on its characteristics of precipitation. It is evident from this study that accurate soil moisture and temperature are few essential ingredients for putting atmosphere-land interactions and associated feedback mechanisms in places for better rainfall predictions particularly from monsoon depressions. Rajesh *et al*. (2017) demonstrated that implementing high resolution land surface assimilation has improved the monsoon depression prediction with special emphasis on its rainfall features and associated dynamics over the Indian region. Prajeesh *et al*. (2013) has shown that the frequency of landfall of monsoon depression on the east coast of India has significantly decreased during 1979-2019 and particularly reduced up to 80% confining to the south of 20° N. Kishtawal *et al*. (2013) has examined more than 400 cases of monsoon low pressure systems formed over Bay of Bengal and found that these low pressure systems are very likely to form on a day during active monsoon state than break state. Further, they have concluded that monsoon depressions with high inland penetration were mainly associated with higher antecedent rainfall. However they found that, there is not much differences in low level atmospheric circulation for monsoon depressions with shortest or longest inland penetration over Indian region.

Dimri *et al*. (2015) extensively highlighted the importance of western disturbance (WD) synoptic systems for Indian weather and climate particularly the winter precipitation over northern India. Dimri and Chevuturi (2013) has shown that upper level trough in eastward moving south tropical easterly jet when merge over the existing stationary lower level cyclonic circulation creates a genesis ground for WD. Dimri (2013) illustrated that the western Himalaya region receives one third of annual precipitation due to eastward moving cyclonic storms and western disturbances (WD) during Indian winter monsoon. In addition they noted that there were significant southward shift of 200 hpa Subtropical Westerly Jet (SWJ) with stationary wave pattern over the Indian region particularly during wet years. Kumar *et al*. (2017) has concluded that WD is the major responsible system for causing unprecedented rainfall over northern Indian and neighbourhood regions. The major mechanism responsible is the intensity of WD as well as the confluence of cold and dry westerlies with warm and moist easterlies over Indian region. Kumar *et al*. (2015) using surface observations for 30 years has advocated that the total winter rainfall including frequency of heavy rainfall days have decreased over the Himachal Pradesh region. They found that decrease is about 25% in heavy rainfall days and 13% in the total winter rainfall over the state.

4. Tropical cyclones

Tropical cyclone is one of the major natural disaster impacting India. Even though the north Indian Ocean (NIO) basins generates only 7% of the world cyclones but often they are very severe storms making landfall on the coastline of India. They are responsible for large scale destructions of properties, loss of livelihood and deaths of the citizens particularly residing in vulnerable coastal areas. Mohapatra *et al*. (2013) has evaluated skills of the operational forecast of IMD with a lead time up to 72 hours during 2003-2011 and found that direct positioning error (DPE) and skills are less compared to northwest pacific and north Atlantic basin. However, they have mentioned that rate of decrease (increase) in DPE (skill) is higher over NIO for the considered study period. The same study with focus on tropical cyclone intensity forecast, noted that no significant improvement in terms of absolute error (AE) and Root Mean Square Error (RMSE) in NIO compared to north-west and Atlantic basin. Das *et al*. (2015) tested Hurricane Weather Research and Forecasting (HWRF) model, which is operationalized at IMD for real time forecast for NIO basin. They found that the average track error of the model varies between 83 km with lead time 12 hours to 319 km at 72 hours. The model showed an improvement of track up to 27% and 15% at the lead time of 48 and 72 hour respectively, however the improvement in the intensity forecast is marginal (5-8%) compared to IMD operational forecast.

Rai *et al*. (2016) has shown that radial distribution of sea surface temperature (SST) has substantial impact on tropical cyclone characteristics particularly on its core structure and intensity. It is found that positive (negative) radial anomaly of SST within the 75 (300) km of the storm core produced the most intense (weakest) storm over the NIO. The strongest storm produced has dominantly influenced by dynamical and thermodynamical features within 2-2.5 times of the radius of maximum wind. Using WRF model, Rai and Pattnaik (2018a) has shown that planetary boundary layer parameterization (PBL) has limited impact on the pre intensification phase of the storm, however significantly impact on tropical cyclone characteristics during its rapid intensification phase. They have found that Boulac (MRF) PBL schemes produced the most intense (weakest) storm over Bay of Bengal. Another important result from this paper is, MRF scheme produced a relatively deeper and drier inflow layer associated with weaker cyclonic vorticity just above the boundary layer reducing the moisture transport and weaken the secondary circulation, hence the storm intensity. Further, Rai and Pattnaik (2018b) have suggest that high resolution SST is an important ingredient for accurate storm intensity forecast for NIO basins.

Bhomia *et al.* (2017) compared four forecast models from global operational forecasting agencies to evaluate their skills up to 72 hours for landfall of tropical cyclones over NIO. They found that though the models able to capture the track forecast reasonably well, however, none of the models are able to replicate the rainfall characteristics of the storm within 600 km radius from the centre. Routray *et al*. (2018) using operational NCUM found that, the model able to reproduce skilful track prediction when initialized at the severe cyclone stage rather cyclonic stage or lower. Further, they have concluded that the model able to predict landfall location with better accuracy compared to landfall time and the model has eastward bias in the tropical cyclone track compared to best track observations over the NIO basins. Rao and Srinivas (2014) made an attempt to provide an ensemble prediction for tropical cyclone over NIO using various physics options available in the WRF model. They found that convective ensemble had the large spread of cluster and boundary layer ensembles has significant dissimilarities in errors. The best ensemble prediction for tropical cyclone was provided by the cloud microphysics ensemble suggesting that inclusion of all different hydrometeors are essential for accurate tropical cyclone forecast for Bay of Bengal. These results highlighting the importance, challenges and complexity of forecast of the tropical cyclone particularly with respect to its genesis, intensity and rainfall for NIO basins.

5. Clouds-aerosol and air quality

There is growing demand in the country to provide rain through cloud seeding to fulfil multiple objectives such as catering drought hit districts where agricultural fields are rain fed, provide water in catchment areas, clearing air pollution from major cities. The massive long term observation campaign initiated by Indian Institute of Tropical Meteorology (IITM) in the name of Cloud Aerosol Interaction and Precipitation enhancement (CAIPEEX) (Kulkarni *et al*., 2012) has been conceived to not only cater to these demands of the emerging society but also to unlock the intriguing and complex information about life cycle of clouds, their interactions with aerosol, ambient environment, large scale and synoptic scale weather systems. Using CAIPEEX observed data sets and WRF Chemistry sensitivity experiments, Dipu *et al*. (2013) showed that an enhanced dust emission scenario with source from Thar desert resulted in an elevated radiative heating over central Indian region and this is mainly attributed to enhanced elevated aerosol layers in lower to middle troposphere (2-5 km). In addition, established that natural dust emissions can significantly influence the spatial and temporal distribution of cloud and associated precipitation and subsequently impacting the hydrological cycle. Recently, Mahesh *et al*. (2018) using CAIPEEX data has shown that majority of monsoon rainfall is due to warm and mixed phase rain processes. Using CAIPEEX observations, Prabha *et al.* (2011) has shown that pre-monsoon clouds are highly polluted with narrower drop size distribution (DSD) compared to monsoon clouds. They have unrevealed the existence of a continuous generation of small droplets to different heights and this leads to bimodal and multimodal distribution of DSD. They have concluded that in cloud nucleation at elevated layers are the main mechanisms for generation of multi modal DSD in monsoon deep convective clouds. Konwar *et al*. (2014) unravel causes of intense rainfall in shallow clouds through interactions of cloud microphysics and dynamics over the western ghat region. They found that break up process of large raindrops are responsible for increase in drop concentration at mid sizes and collision, coalescence processes are dominated over the region. In addition, it is noted that, there is sustained interactions between cloud mass and ambient orographic updrafts facilitating rapid condensational growth of cloud droplets. Through this program, it is evident that many new insights have been added to augment our understanding about complex interactions among cloud, aerosol and ambient environment and their impact on convection and rainfall over India.

Sarangi *et al*. (2018) has shown the cooling impact of cloud aerosol interactions at surface and top of the atmosphere and also suggested that aerosols have the major influence on inducing cloud invigoration effect over ISM region. Previously, the same group has also found that aerosol loading over Indian region has a strong correlation with cloud fraction as well as monsoon rainfall and they have shown that higher aerosol loading can invigorate monsoon deep cloud systems leading to an enhancement in precipitation over Indian region (Sarangi *et al*., 2017). Kumari *et al*. (2007) has noted a solar dimming scenario over India using 24 years of surface observations from 12 stations spread across India. The magnitude of solar dimming is about 0.86 W/m^2 per year and has respective dimming rate in different seasons are 0.94, 1.04 and 0.74 W/m^2 for winter, pre-monsoon and monsoon seasons respectively. However, they have further argued that in spite of drastic reduction in solar insolation, all Indian averaged surface maximum and minimum air temperature have been increasing and mainly attributed to the increase in greenhouse gas emissions. Govardhan *et al*. (2015) found that the WRF-Chemistry model systematically underestimates near-surface black carbon mass concentrations as well as columnar Aerosol Optical Depths (AODs) from the measurements over Indian region. The reason attributed to this behaviour is over estimation of PBL height and surface wind speeds causing deeper mixing and dispersion and hence lowering the surface concentration of aerosol over India. They have concluded with suggestion that better aerosol prediction can only be possible if better meteorology can be simulated by the model. Hazra *et al*. (2013) examined the role of aerosol to understand transitioning of break to active conditions of monsoon and found that break followed by active condition are dominated by higher concentration of absorbing aerosols leading to an intense north-south low level temperature gradient and moisture convergence. These conditions are facilitating forced uplift beyond freezing level and initiating cold rain process at higher level simulating convection and rainfall. Kumar *et al*. (2014) suggested the presence of enhanced cloud liquid water and giant cloud condensation nuclei dominate warm rain process in the Western Ghat region, whereas more cloud ice, snow and graupel over Myanmar coast, where cold rain is evolving from the mixed phase processes. Further they have highlighted the representation of mixed phase processes is one of the major uncertainties in General circulation models. Hazra *et al*. (2016) found that microphysical process such as cloud to rain water auto-conversion, snow and rain accretion are the dominant processes impacting the cloud hydrometeors and precipitation characteristics at monsoon intraseasonal oscillations timescale over the Indian region. They further emphasized that detailed cloud microphysical production rates for warm and mixed phase processes are the major sources of uncertainties in the climate models and it is essential that better understanding and accurate representation of improvement of these fine scale processes are essential to enhance confidence in climate predictions.

One major initiative entitled the System of Air quality Forecasting And Research (SAFAR) project was started in year 2010 was taken up by IITM to address emerging air quality issues particularly over the major cities in the country. The objective of this program is to observe, understand and forecast air quality related issues of urban locations. Initially targeted for Tier-I (major) cities and subsequently the program will be expanded to other cities in the country. In the initial phase, project has deployed both meteorological and air quality observation sensors across the major cities in the countries (*i.e*., Delhi, Pune, Ahmedabad and Mumbai) and measuring PM10, PM2.5, aerosols, reactive trace gases. In addition, providing real time forecast products of the air quality for these cities from now casting to short range temporal scale through user friendly app based applications and through large display systems for common public (Beig *et al*., 2015).

6. Severe weather systems

Goswami *et al*. (2006) has shown an increasing trend of extreme rainfall events over central India. Though later studies (Ghosh *et al*., 2009, 2012) demonstrated disparity and in homogeneity in the trends of extreme rainfall over Indian region, however number of research results are coherent in their view that the frequency as well as intensity of severe weather systems are increasing over India. Using high resolution (0.25 × 0.25) gridded data sets Vinnarasi and Dhayna (2016) has shown that there is a significant increase in the maximum intensity of rainfall and spatial heterogeneity has been noted for past half century within their analysis of 113 years. They have also noted a shift in the frequency of distribution of extreme rainfall events during the monsoon period and significant negative trends in wet spell durations and positive trends in dry spell durations. Dash *et al*. (2011) has found that, the frequency of short spell rain events with heavy intensity have increased and long spell rain events with moderate to low intensities have decreased over India. Further, they found that short spell heavy to moderate intensity rain events have increased its contribution to the seasonal rainfall. Recently, Roxy *et al*. (2017) has shown threefold increase in extreme rainfall event over Indian region and this has been attributed to surge in monsoon westerlies, facilitating the enhanced moisture incursion to the Indian region. Baisya and Pattnaik (2019) investigated the Kerala heavy rainfall event of year 2018 and noted that multiple factors such as western ghat orography, anomalous transportation of moisture through monsoon flow, traversing of moisture flux convergence towers from a monsoon depression over eastern India to the Kerala region and positive quasi bi-weekly/Intra seasonal oscillations are working in tandem for making this kind of severe heavy rainfall situation.

Using gridded temperature data sets, Ross *et al*. (2018) has shown that there is a consistent warming pattern is found over northwestern and southern India and a pattern of cooling was noted over the northeastern and southwestward regions of India. The pattern of warming has been attributed to the global warming scenario and cooling due to large scale present of haze and aerosol over the region. Mukherjee and Mishra (2018) recently found that there is a significant increase in 1 and 3-day concurrent hot day and hot night events over India. They have used model simulations from climate of 20th century plus detection and attribution and coupled model inter-comparsion project 5 (CMIP5). Further, they have suggested that restricting global mean temperature below 1.5 from the pre-industrial level may substantially reduce the risk of 1 to 3 day concurrent hot day and hot night events over India. Mishra *et al.* (2017) has shown that if the global mean temperature is limited to 2.0 °C above pre-industrial era, there are chances that frequency of severe heat waves might increase by 30 times the current climate scenarios over Indian region. Using 30 years data sets, Keval and Pattnaik (2019), has noted that the daily maximum, minimum and mean temperature has increased at the rate of 0.006 °C, 0.012 °C and 0.017 °C per year, respectively in the districts of western Odisha and neighboring Chhattisgarh. Further, they noted that, over these regions, frequency and intensity of warm nights have increased, whereas frequency and intensity of cold nights have decreased over the years. Dash and Mamgain (2011) using IMD data sets have shown that there is a significant decrease in frequency of occurrence of cold nights in the winter months in India and in its homogeneous regions in north except over western Himalaya. Additionally, they have found that southern regions of India shows a drastic decrease in frequency of cold nights and increase in warm nights over the interior peninsula regions with highest region of warming over west coast of India. Ali and Mishra (2017) proposed that a strong positive relationship found between dew point and tropospheric temperature with rainfall extremes over urban locations in India. They have also suggested that surface air temperature might not be ideal parameters to examine the extreme rainfall cases over urban locations.

For extreme rainfall case of Mumbai (2005), Bhaskar Rao and Ratna (2010) has shown that National Centre for Atmospheric Research (NCAR) MM5 model with analysis nudging for 12 hour could able to reproduce best simulation results up to 55 cm of rainfall in 24 hours at correct location of Mumbai. They have noted that intense monsoon westerlies at the lower level with dry air incursion at the middle level suppressed convection and leading to enhanced potential instability at lower levels causing this cloud burst situation. Madala *et al.* (2014) simulated few thunderstorm events over Gadanki using WRF model with an aim to understand the impact of PBL parameterization on these events. They noted that Mellor-Yamada-Janjic (MYJ), scheme produced the best thunderstorm and MYJ-Grell-Devenyi ensemble scheme (GD) combination captured the vertical extent of the convective updraft but the event has lag and lead of one and half hour than observed. Halder *et al*. (2015) discussed about role of better ice nucleation process and their impact on realistic representation of severe thunderstorm over Indian region. They have suggested that improvement in cloud ice generation has positive impact on cloud microphysics and associated dynamics through latent heat release and leading to improvement in thunderstorm prediction. Sisodiya *et al*. (2019) has demonstrated that using high resolution improved land assimilation system, it is possible to improve the location specific severe thunderstorm event over the state of Odisha. Rajeevan *et al*. (2010) has undertaken a study to assess the impact of cloud microphysics on thunderstorm and concluded that there are major disparities among simulations due to different cloud microphysics parameterization. All the four microphysics schemes underestimated strength and vertical extend of updraft and lacks in replicating the downdrafts of the storm. They have concluded with strong emphasis on carrying out intense observational campaign targeting to understand cloud microphysical and land surface processes over Indian region. Rajesh *et al*. (2016) has demonstrated that high resolution model with improvement in land state conditions over Indian region can better simulate the intense rainfall event to understand these high impact weather system such as Uttarakhand event of 2013. It is found that accurate representation of land state with special reference to soil moisture and temperature, leading to unravel the channel of continuous supply of moisture incursion from Arabian Sea to the Uttarakhand region aggravating the intensity of the event. Dimri *et al*. (2017) in a review article identified that, combination of factors such as large scale & small scale meteorological forcings, orographic influence and geomorphological conditions are responsible for cloud burst events over Himalayan region. Majority of these events occurred at the elevation range of 1000 m to 2500 m within the valley folds of the southern rim of the Indian Himalayas. Murugavel *et al*. (2014), suggested that convective available potential energy might be the only factor responsible for pre-monsoon lightning events. They found that prevailing meteorological conditions along with regional orography playing a major role in inducing lightning activity over India. Pawar *et al*. (2017) found that in pre-monsoon thunderstorm inverted polarity charge structure of the storm has a good correlation with the dew point depression. In addition, they have noted that the high aerosol concentration with adequate ice nuclei plays a dominant role in inverted polarity charge structure in thunderclouds.

7. Data and observation campaign

High resolution spatio-temporal observation data is one of the major challenges for the weather and climate researchers for accurate understanding of the physical processes, validation of model results and to provide an authenticate representation of climate change scenario over the Indian region. Therefore, reliable long term observation data is key for the progress of weather and climate science in India. Rajeevan *et al.* (2006) has developed a gridded daily rainfall data at 1° × 1° horizontal resolution taking surface observations from 1803 stations across the country. These data is considered as one of the benchmark data sets for rainfall observations over India and extensively used by the research community and operational agencies across the globe for various purpose. This effort has been augmented by Pai *et al.* (2013, 2014) by bringing out high resolution daily rainfall data at a spatial resolution of 0.25° × 0.25° over Indian main land. They have considered about 6955 rain gauge station for developing this data sets. This data set is now extremely popular and authenticated by several researchers in terms of its representativeness and accuracy. Further, Mitra *et al.* (2009, 2013) had developed a moderate resolution (1° × 1°) daily rainfall data sets through merging of satellite rainfall dataset [e.g., Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Measurement (GPM] along with estimates from IMD rain gauge. This data is immensely popular among research community across India and the globe due to additional information of local gauge rainfall data and rainfall estimates are available over the oceanic regions. In this segment, the high resolution outgoing longwave radiation (OLR) data developed at 0.25° × 0.25° resolution by Mahakur *et al.* (2013) has potential to provide information about cloud types causing rainfall and facilitate in unravelling convective cloud organization from mesoscale to synoptic scale over the Indian region. Apart from these specific data sets, plethora of different atmospheric and ocean data sets were obtained from observation campaign, satellites and remote sensing instruments are readily available in IMD, Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC), Indian Space Research Organization (ISRO), IITM Pune and Indian National Centre for Ocean Information Services (INCOIS) for researchers for carrying out research and development activities.

Indian research community has taken lead in initiating several targeted observational campaigns with specific scientific questions relevant to the country in recent years. To name a few, Cloud-Aerosol Interactions and Precipitation Enhancement Experiment (CAIPEEX), Interaction of Convective Organization and Monsoon Precipitation, Atmosphere, Surface and Sea (INCOMPASS), South West Asian Aerosol - Monsoon Interactions (SWAAMI), Forecast Demonstration Project on Cyclone (Raj *et al*., 2010), Pre-monsoon SAARC Severe Thunderstorm observation and regional modelling (STORM) project (Ray *et al*., 2015), Continental Tropical Convergence Zone (CTCZ) (DST, 2008). These massive observation campaigns under the national monsoon mission program will surely prove to be a milestone in achieving desired objectives of the outstanding scientific challenges in weather and climate sciences in coming years through enriching scientific community with rare and valuable observation and modelling data sets. Each of these observation campaign has been oriented towards specific scientific questions, region/duration of observations, deployment of observation equipment and modelling framework. These efforts are multi institutional and multidisciplinary in nature, hence requires massive and sustained co-ordination in terms of science, planning, logistics, administration and timely execution. Successful completion of these observation campaigns, has highlighted the point that India has developed indigenous capabilities and authorities to take up these emerging challenges in future with an aim to understand and unravel finer details of many intriguing science questions related to monsoon and other important weather systems over the region. These vital information in terms of observations can be subsequently used in terms of data assimilation, accurate representation of physical processes, validations of the models with aim to improve their forecast skills at different spatio-temporal resolution for diverse weather and climate systems over the Indian region.

8. Way forward

India has progress leaps and bounds in weather and climate science research accomplishments in recent decades and at par with leading developed countries of the world. Here, few challenging gap areas are identified, which we should focus and address in coming years to prepare ourselves well for emerging challenges in weather and climate sciences in the country.

(*i*) In the climate change scenario, there is an increase in weather and climate extreme events over India. Therefore, more emphasize should be given to develop better early warning systems for societal preparedness and put intense efforts in terms of observation, modelling and validation for accurate identification and understanding of key physical processes over vulnerable regions responsible for causing these extreme events.

(*ii*) The thrust must be on developing and adapting state of art tools, models and emerging techniques such as artificial intelligence, machine learning, augmented and virtual reality and other digital framework not only to generate forecast but also to customized and disseminate region specific information for different kind of weather systems over the targeted area.

(*iii*) Though fundamental research is the backbone of any science, however, researchers must be encouraged to adapt and channelize their research objectives towards fulfilling the immediate needs and upcoming demands of the society in the weather and climate services.

(*iv*) Keeping our country's need, major grand challenges in weather and climate services must be identified & feasible roadmap to achieve those objectives in short term and long term time scale should be prepared.

(*v*) More high density observation facilities must be established in the country in terms of test beds, observatories for validation and long term unbiased time series data. Further, more research is required to explore cost effective unmanned aerial vehicle (UAV) procedure to assess the value of obtaining observations for intense weather systems in remote areas over land as well as ocean in order to improve models.

(*vi*) A fresh and innovative approach should be adapted by the operational and research agencies for data collection, archival and dissemination to provide a seamless, thriving and vibrant research ecosystem to the academicians, scientists and students in country.

(*vii*) Sustainable framework needs to be built for engaging high quality skilled manpower in weather and climate sciences to maintain the momentum of improving our capabilities to find solutions to the outstanding problems & develop better models with reasonable forecast accuracy with adequate lead time for the benefits of citizens.

(*viii*) It is essential to adapt a culture where academician, researcher, forecaster, relevant agencies and other stake holders should work coherently and continuously as a team to not only review the existing weather and climate services in the country but also to come out with innovative strategies to effective address the evolving challenges.

(*ix*) An interface must develop to continuous formulate methods to incorporate the observational understanding to the modelling framework.

(*x*) Apart from thrust areas discussed in the article few other areas needs attention such as renewal energy, climate change and regional climate variability, extreme events, lightning & thunderstorm, land-atmosphere-ocean coupling, acute air pollution, hail and dust storms, weather modification and geo engineering may be emphasized.

Sustained efforts and discipline practices in these direction will enable our scientists and researchers to meet grand challenges of our society and prepare themselves well to adapt to the growing demands in weather and climate services of India in the 21st century. Finally, author humbly admit that there are plentiful path breaking research activities carried out by Indian scientists in recent decades, however due to restriction in preparation of this document few are highlighted here. It is anticipated that, this blend of knowledge and information will supplement our policy makers and administrators to improve decision support systems for the benefits of the citizens.

Acknowledgement

Author extends its gratitude to Dr. K. J. Ramesh, Director General, IMD for invitation and encouragement to write this article. Author is grateful to IIT Bhubaneswar for providing necessary infrastructure and support. The majority of these research accomplishment made in the country is directly or indirectly supported by leading funding agencies such as Ministry of Earth Sciences (MoES), Department of Science Technology (DST), Indian Space Research Organization (ISRO), Science and Engineering Research Board (SERB), Council of Scientific and Industrial Research (CSIR) and many centrally/state funded institutes and research organizations, author is grateful to these agencies for sustained support and encouragement to our researchers for carrying out these scientific activities. Author pay deepest tribute to Prof. T. N. Krishnamurti and Shri D. R. Sikka and dedicate this article to these legends. They will be eternally remembered and will inspire generations of meteorology fraternity for their vast contribution towards weather and climate research in India.

The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of their organizations.

References

Abhilash, S., Sahai, A. K., Borah, N., Chattopadhyay, R., Joseph, S., Sharmila, S., De, S., Goswami, B. N. and Kumar, Arun, 2014, "Prediction and Monitoring of Monsoon Intra-seasonal Oscillations over Indian monsoon region in an Ensemble Prediction System using CFSv2", *Climate Dynamics*, **42**, 9-10, 2801-2815, doi:10.1007/ s00382-013-2045-9.

Ali, H. and Mishra, V., 2017, "Contrasting response of rainfall extremes to increase in surface air and dewpoint temperatures at urban locations in India", *Scientific Reports*, **7**, p1228.

Anand, Abhishek, Mishra, Saroj K., Sahany, Sandeep, Bhowmick, Mansi, Rawat, Janmejai Singh and Dash, S. K., 2018, "Indian

Summer Monsoon Simulations: Usefulness of Increasing Horizontal Resolution Manual Tuning and Semi-Automatic Tuning in Reducing Present-Day Model Biases", *Scientific Reports*, **8**, p3522. DOI:10.1038/s41598-018-21865-1.

Baisya, H. and Pattnaik, S., 2019, "Orographic effect and multiscale interactions during an extreme rainfall event", *Environmental Research Communications*, **1**, 5, https://doi.org/10.1088/2515-7620/ab2417

Baisya, H., Pattanaik, S. and Rajesh, P. V., 2017, "Land surface-precipitation feedback analysis for a landfalling monsoon depression in the Indian region", *Journal of Advances in Modeling Earth Systems*, **9**, 712-726, doi:10.1002/2016MS000829.

Baisya, H., Pattnaik, S., Hazra, V., Sisodiya, A. and Rai, D., 2018, "Ramifications of Atmospheric Humidity on Monsoon Depressions over the Indian Subcontinent", *Scientific Reports*, **8**, 9927, https://www.nature.com/articles/ s41598-018-28365-2.

Beig, G., Dilip, M. Chate, Sahu, Saroj K., Parkhi, Neha S., Srinivas, Reka, Ali, Kausar, Ghude, Sachin D., Yadav, Sarita and Trimbake, Hanumant K., 2015, "System of Air Quality Forecasting and Research (SAFAR - India)", World Meteorological Organization Global Atmosphere Watch, GAW Report No. 217, WMO.

Bhaskar Rao, D. V. and Ratna, S. B., 2010, "Mesoscale characteristics and prediction of an unusual extreme heavy precipitation event over India using a high resolution mesoscale model", *Atmospheric Research*, **95**, 255-269.

Bhaskar Rao, D. V. and Srinivas, D., 2014, "Multi-Physics ensemble prediction of tropical cyclone movement over Bay of Bengal", *Nat. Hazards*, **70**, 883-902. DOI 10.1007/s11069-013-0852-2.

Bhomia, S., Jaiswal, N. and Kishtawal, C. M., 2017, "Accuracy assessment of rainfall prediction by global models during the landfallof tropical cyclones in the North Indian Ocean", *Meteorological Applications*, **24**, 503-511.

Das, A. K., Rama Rao, Y. V., Tallapragada, Vijay, Zhang, Zhan, Roy Bhowmik, S. K. and Sharma, Arun, 2015, "Evaluation of the Hurricane Weather Research and Forecasting (HWRF) model for tropical cyclone forecasts over the North Indian Ocean (NIO)", *Nat. Hazards*, **75**, 1205-1221.

Dash, S. K. and Mamgain, Ashu, 2011, "Changes in the frequency of different categories of temperature extremes in India", *Journal of Appl. Met. and Clim*., **50**, 1842-1858.

Dash, S. K., Nair, Archana Anil, Kulkarni, Makarand A. and Mohanty, U. C., 2011, "Characteristic changes in the long and short spells of different rain intensities in India", *Theor. Appl. Climatol*., **105**, 5-6, 563-570.

Dimri, A. P. and Chevuturi, A., 2013, "Model sensitivity analysis study for Western Disturbances over the Himalayas", *Meteorol. Atmos. Phys*., **123**, 3-4, 155-180.

Dimri, A. P., 2013, "Interannual variability of Indian winter monsoon over the Western Himalayas", *Global and Planetary Change*, **106**, 39-50.

Dimri, A. P., Chevuturi, A., Niyogi, D., Thayyen, R. J., Ray, K., Tripathi, S. N., Pandey, A. K. and Mohanty, U. C., 2017, "Cloudbursts in Indian Himalayas: A review", *Earth-Science Reviews*, **168**, 1-23.

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C, Yasunari, T. and Sikka, D. R., 2015, "Western Disturbances: A review", *Rev. Geophys*., **53**, 225-246, doi:10.1002/2014 RG000460.

Dipu, S., Prabha, Thara V., Pandithurai, G., Dudhia, J., Pfister, G., Rajesh, K. and Goswami, B. N., 2013, "Impact of elevated aerosol layer on the cloud macrophysical properties prior to monsoon onset", *Atmospheric Environment*, **70**, 454-467.

DST, 2008, "Continental Tropical Convergence Zone (CTCZ) Programme: Science Plan", Department of Science and Technology, New Delhi, India, p167.http://odis.incois.gov.in/images/ctczimages/docs/science_plan.pdf.

George, G., Rao, Nagarjuna, D., Sabeerali, C. T., Srivastava, Ankur and Rao, Suryachandra A., 2016, "Indian summer monsoon prediction and simulation in CFSv2 coupled model", *Atmos. Sci. Let.*, **17**, 57-64.

Ghosh, S., Das, Debasish, Kao, Shih-Chieh and Ganguly, Auroop R., 2012, "Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes", *Nature Climate Change*, **2**, 86-91, doi: 10.1038/nclimate1327.

Ghosh, S., Luniya, Vishal and Gupta, Anant, 2009, "Trend analysis of Indian summer monsoon rainfall at different spatial scales", *Atmos. Sci. Let.*, **10**, 285-290.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S. and Xavier, P. K., 2006, "Increasing trend of extreme rain events over India in a warming environment", *Science*, **314**, 1442-1445.

Govardhan, Gaurav, Nanjundiah, Ravi S., Satheesh, S. K., Krishnamoorthy, K. and Kotamarthi, V. R., 2015, "Performance of WRF-Chem over Indian region", *J. Earth Syst. Sci.*,**124**, 4, 875-896.

Haldar, M., Hazra, Anupam, Mukhopadhyay, P. and Singh, Devendraa, 2015, "Effect of the better representation of the cloud ice-nucleation in WRF microphysics schemes: A case study of a severe storm in India", *Atmospheric Research*, **154**, 155-174.

Hazra, A., Chaudhari, H. S., Pokhrel, S. and Saha, S. K., 2016, "Indian summer monsoon precipitating clouds: role of microphysical process rates", *Climate Dynamics*, **46**, 7-8, 2551-2571, doi: 10.1007/s00382-015-2717-8.

Hazra, A., Goswami, B. N. and Chen, J. P., 2013, "Role of interactions between aerosol radiative effect, dynamics and cloud microphysics on transitions of monsoon intraseasonal oscillations", *Jr. Atmos. Sci*, **70**, 2073-2087.

Jain, D., Chakraborty, A. and Nanjundaiah, Ravi S., 2018, "A mechanism for the southward propagation of mesoscale convective systems over the Bay of Bengal", *Journal of Geo. Research Atmospheres*, **123**, 8, 3893-3913, https://doi.org/10.1002/ 2017JD027470.

Joseph, S., Sahai, A. K., Sharmila, S., Abhilash, S., Borah, N., Chattopadhyay, R. and Kumar, A., 2015, "North Indian heavy rainfall event during June 2013: Diagnostics and extended range prediction", *Climate Dynamics*, **44**, 7-8, 2049-2065.

Keval, M. and Pattnaik, S., 2019, "Spatio temporal patterns of surface temperature over western Odisha and eastern Chattisgarh", *SN App. Sci.*, **1**, 991, https://doi.org/10.1007/s42452-019-0986-2.

Kishtawal, C. M., Niyogi, Dev, Rajagopalan, Balaji, Rajeevan, M., Jaiswal, N. and Mohanty, U. C., 2013, "Enhancement of inland penetration of monsoon depressions in the Bay of Bengal due to prestorm ground wetness", *Water resources research*, **49**, 3589-3600, doi:10.1002/wrcr.20301.

Konwar, M., Das, S. K., Deshpande, S. M., Chakravarty, K. and Goswami, B. N., 2014, "Microphysics of clouds and rain over the Western Ghat", *J. Geophy. Res.*, **19**, 1-20, doi:10.1002/2014JD021606.

Koul, V., Parekh, A., Srinivas, G., Kakatkar, R., Chowdary, J. S. and Gnanaseelan, C., 2018, "Role of ocean initial conditions to diminish dry bias in the seasonal prediction of Indian summer monsoon rainfall: A case study using climate forecast system", *Journal of Advances in Modeling Earth Systems*, **10**, 1-14, https://doi.org/10.1002/2017MS001129.

Krishnan, K., Zhang, C. and Sugi, M., 2000, "Dynamics of breaks in the Indian summer monsoon", *Journal of the Atmospheric Sciences*, **57**, 1354-1372.

Kulkarni, J. R., Mahesh kumar, R. S., Morwal, S. B., Padma kumara, B., Konwar, M., Deshpande, C. G., Joshi, R. R., Bhalwankar, R. V., Pandithurai, G., Safai, P. D., Narkhedkar, S. G., Dani, K. K., Nath, A., Nair, Sathy, Sapre, V. V., Puranik, P. V., Kandalgaonkar, S. S., Mujumdar, V. R., Khaladkar, R. M., Vijaykumar, R., Prabha, T. V. and Goswami, B. N., 2012, "Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX): overview and preliminary results", *Current Science*, **102**, 413-425.

Kumar, N., Mohapatra, M. and Jaswal, A. K., 2017, "Meteorological features associated with unprecedented precipitation over India during 1st week of March 2015", *J. Earth Syst. Sci.*, **126**, 62, doi:10.1007/s12040-017-0842-y.

Kumar, N., Yadav, B. P., Gahlot, S. and Singh, M., 2015, "Winter frequency of western disturbances and precipitation indices over Himachal Pradesh, India: 1977-2007", *Atmosfera*, **28**, 1, 63-70.

Kumar, S., Hazra, A. and Goswami, B. N., 2014, "Role of interaction between dynamics, thermodynamics and cloud microphysics on summer monsoon precipitating clouds over the Myanmar coast and the western Ghats", *Clim. Dyn.*, **43**, 3-4, 911-924, doi:10.1007/s00382-013-1909-3,911-924.

Kumari, Padma B., Londhe, A. L., Daniel, S. and Jadhav, D. B., 2007, "Observational evidence of solar dimming: Offsetting surface warming over India", *Geophysical Research Letters*, **34**, 21, L21810, doi: 10.1029/2007GL031133.

Madala, S., Satyanarayana, A. N. V. and Rao, T. Narayana, 2014, "Performance evaluation of PBL and cumulus parameterization schemes of WRFARW model in simulating severe thunderstorm events over Gadanki MST radar facility-Case study", *Atmospheric Research*, **139**,1-17.

Mahakur, M., Prabhu, A., Sharma, A. K., Rao, V. R., Senroy, S., Singh, Randhir and Goswami, B. N., 2013, "A high-resolution outgoing longwave radiation dataset from Kalpana-1 satellite during 2004-2012", *Current Science*, **105**, 8, 1124-1133.

Mahesh Kumar, R. S., Padmakumari, B., Konwar, Mahen, Morwal, S. B. and Deshpande, C. G., 2018, "Characterization of hydrometeors and precipitation over the Indian monsoon region using aircraft measurements", *Atmospheric Research*, **205**, 147-154.

Mishra, V., Mukherjee, S., Kumar, R. and Stone, D. A., 2017, "Heat wave exposure in India in current, 1.5 °C and 2.0 °C worlds", *Environmental Research Letters*, **12**, 124012, https://doi.org/10.1088/ 1748-9326/aa9388.

Mitra, A. K., Bohra, A. K., Rajeevan, M. N. and Krishnamurti, T. N., 2009, "Daily Indian precipitation analyses formed from a merged of rain-gauge with TRMM TMPA satellite derived rainfall estimates", *Journal of the Meteorological Society of Japan*, **87A**, 265-279.

Mitra, A. K., Momin, I. M., Rajagopal, E. N., Basu, S., Rajeevan, M. N. and Krishnamurti, T. N., 2013, "Gridded daily Indian monsoon rainfall for 14 seasons: Merged TRMM and IMD gauge analyzed values", *J. Earth Syst. Sci.*, **122,** 5, 1173-1182.

Mohapatra, M., Nayak, D. P., Sharma, R. P. and Bandyopadhyay, B. K., 2013, "Evaluation of official tropical cyclone track forecast over north Indian Ocean issued by India Meteorological Department", *J. Earth Syst. Sci*., **122**, 3, 589-601.

Mukherjee, S. and Mishra, Vimal, 2018, "A sixfold rise in concurrent day and night-time heat waves in India under 2 °C warming", *Scientific Reports*, **8**, 16922, doi:10.1038/s41598-018-35348-w.

Mukhopadhyay, P., Taraphdar, S., Goswami, B. N. and Kumar, K. Krishna, 2010, "Indian summer monsoon precipitation climatology in a high resolution regional climate model: Impact of convective parameterization on systematic biases", *Weather Forecast*., **25**, 369-387, doi:10.1175/2009WAF2222320.1.

Murugavel, P., Pawar, S. D. and Gopalakrishan, V., 2014, "Climatology of lightning over Indian region and its relationship with convective available potential energy", *International Journal of Climatology*, **34**, 11, 3179-3187.

NOAA and MoES, MoU, 2011, "Implementing Agreement on Technical Cooperation for the Study of Dynamical Seasonal Prediction of Indian Summer Monsoon Rainfall between the National Oceanic and Atmospheric Administration of the Government of the United States of America and the Ministry of Earth Sciences of the Government of the Republic of India", (https://www.state.gov/documents/ organization/161680.pdf).

Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S. and Mukhopadhyay, B., 2013, "Development and analysis of a new high spatial resolution (0.25° × 0.25°) long period (1901-2010) daily gridded rainfall data set over India Rep.", National Climate Centre, India Meteorological Department, Pune, India.

Pai, D. S., Sridhar, L., Rajeevan, M., Sreejith, O. P., Satbhai, N. S. and Mukhopadhyay, B., 2014, "Analysis of daily rainfall events over India using a new long period (1901-2010) high resolution (0.25° × 0.25°) gridded rainfall data set", *Mausam*, **65**, 1, 1-18.

Pattnaik, S., Abhilash, S., De, S., Sahai, A. K., Phani, R. and Goswami, B. N., 2013, "Influence of convective parameterization on the systematic errors of Climate Forecast System (CFS) model over the Indian monsoon region from an extended range forecast perspective", *Clim. Dynamics*, **44**, 2, 341-365, doi:10.1007/s00382-013-1662-7

Pattnayak, K. C., Panda, S. K., Saraswat, Vaishali and Dash, S. K., 2018, "Assessment of two versions of regional climate model in simulating the Indian Summer Monsoon over South Asia CORDEX domain", *Climate Dynamics*, **50**, 3049-3061.

Pawar, S. D., Gopalakrishnan, V., Murugavel, P., Veremey, N. E. and Sinkevich, A. A., 2017, "Possible role of aerosols in the charge structure of isolated thunderstorms", *Atmospheric Research*, **183**, doi:10.1016/j.atmosres.2016.09.016, 331-340.

Prabha, T. V., Khain, A., Mahesh kumar, R. S., Pandithurai, G., Kulkarni, J. R., Konwar, M. and Goswami, B. N., 2011, "Microphysics of pre-monsoon and monsoon clouds as seen from in situ measurements during CAIPEEX", *J. Atmos. Sci.*, **68**, 1882-1901, doi:10.1175/2011JAS3707.1.

Pradhan, M., Suryachandra Rao, A., Srivastava, A., Dakate, A., Salunke, K. and Shameera, K. S., 2017, "Prediction of Indian Summer-Monsoon Onset Variability: A Season in Advance", *Scientific Reports*, **7**, 14229, https://www.nature.com/articles/s41598-017-12594-y.

Prajeesh, A. G., Ashok, K. and Rao, D. B., 2013, "Falling Monsoon Depression Frequency: A Gray-Sikka Conditions Perspective", *Scientific Reports*, **3**, 2989, https://doi.org/ 10.1038/srep02989.

Rai, D. and Pattnaik, S., 2018a, "Sensitivity of Tropical Cyclone Intensity and Structure to Planetary Boundary Layer Parameterization", *Asia Pacific Journal of Atmospheric Sciences*, **54**, 3, 473-488, https://link.springer.com/article/ 10.1007%2Fs13143-018-0053-8.

Rai, D., Pattnaik, S. and Rajesh, P. V., 2016, "Sensitivity of tropical cyclone characteristics to the radial distribution of sea surface temperature", *J. Earth Syst. Sci.*, **125**, 4, 691-708, doi:10.1007/ s12040-016-0687-9.

Rai, D., Pattnaik, S., Rajesh, P. V. and Hazra, V., 2018b, "Impact of high resolution SST on tropical cyclone characteristics over Bay of Bengal using model simulations", *Meteorological Applications*, **26**, 130-139, https://rmets.onlinelibrary.wiley.com/doi/pdf/ 10.1002/met.1747.

Raj, Y. E. A., Balachandran, S., Ramanathan, R. M. A. N., Geetha, B., Ramesh, K., Selvam, N., Guhan, M. V. and Rajanbabu, D., 2010, "Forecast Demonstration Project (cyclone)-2010", IMD Report, http://www.imdchennai.gov.in/wxSummFinal.pdf.

Rajagopal, E. N., Iyengar, G. R., George, John P., Gupta, Das, Munmun, Saji, Mohandas, Siddharth, Renu, Gupta, Anjari, Chourasia, Manjusha, Prasad, V. S., Sharma, Aditi, Kuldeep Sharma and Amit, Ashish, 2012, "Implementation of Unified Model based Analysis-Forecast System at NCMRWF", NCMRWF Technical Report, NMRF/TR/2/2012.

Rajagopal, E. N., Iyengar, G. R., Mitra, A. K., Prasad, V. S., Gupta, M. Das, George, John P., Kumar, Preveen D., Saji, Mohandas, Ashrit, R. and Dube, A., 2014, "Recent Advances in Numerical Weather Prediction", *Vayu Mandal*, 19-31, imetsociety.org/wp-content/pdf/vayumandal/2014/2014_2.pdf.

Rajeevan, M., Bhate, J., Kale, J. D. and Lal, B., 2006, "High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells", *Curr. Sci.*, **91**, 3, 296-30.

Rajeevan, M., Kesarkar, A., Thampi, S. B., Rao, T. N., Radhakrishna, B. and Rajasekhar, M., 2010, "Sensitivity of WRF cloud microphysics to simulations of a severe thunderstorm event over Southeast India", *Ann. Geophys.*, **28**, 603-619.

Rajeevan, M., Unnikrishnan, C. K., Bhate, Jyoti, Kumar, K. Niranjan and Sreekala, P. P., 2012a, "Northeast monsoon over India: variability and prediction", *Meteorol. Appl.*, **19**, 226-236.

Rajesh, P. V., Pattnaik, S., Rai, D., Osuri, K. K., Mohanty, U. C. and Tripathy, S., 2016, "Role of land state in a high resolution mesoscale model for simulating the Uttarakhand heavy rainfall event over India", *Journal of Earth System Science*, **125**, 3, 475-498, doi:10.1007/s12040-016-0678-x.

Rajesh, P. V., Pattnaik, S., Mohanty, U. C., Rai, D., Baisya, H. and Pandey, P. C., 2017, "Land surface sensitivity of monsoon depressions formed over Bay of Bengal using improved high-resolution land state", *Dynamics of Atmospheres and Oceans*, **80**, 155-172, https://doi.org/10.1016/ j.dynatmoce.2017.10.007.

Ray, K. Bandopadhyay, B. K., Sen, B., Sharma, P., Warsi, A. H., Mohapatra, M., Yadav, B. P., Debnath, G. C., Stella, S., Das. S., Duraisamy, M., Rajeev, V. K., Barapatre, V., Paul, S., Shukla, P., Madan, R., Goyal, S., Das, A. K., Bhan, S. C., Chakravarthy, K. and Rathore, L. S., 2015, "Pre-monsoon thunderstorms 2015", No. ESSO/IMD/SAARC STORM PROJECT-2015/(01)(2015)/4.

Ross, R., Krishnamurti, T. N., Pattnaik, S. and Pai, D. S., 2018, "Decadal surface temperature trends in India based on a new high-resolution data set", *Scientific Reports*, **8**, 7452, doi:10.1038/ s41598-018-25347-2.

Routray, A., Dutta, D. and George, J. P., 2018, "Evaluation of track and intensity prediction of tropical cyclones over North Indian Ocean Using NCUM Global Model", *Pure Appl. Geophys.*, **176**, 1, 421-440, https://doi.org/10.1007/s00024-018-1924-8.

Roxy, M. K., Ghosh, S., Pathak, A., Athulya, R., Terray, P., Murtugudde, R., Mujumdar, M. and Rajeevan, M., 2017, "A threefold rise in widespread extreme rain events over central India", *Nat. Commun.*, **8**, 708, 1-11,DOI: 10.1038/s41467-017-00744-9.

Saha, S. K., Pokhrel, S., Chaudhari, H. S., Dhakate, A., Shewale, S., Sabeerali, C. T., Salunke, K., Hazra, A., Mahapatra, S. and Rao, S. A., 2014, "Improved simulation of Indian summer monsoon in latest version of NCEP Climate Forecast System free run", *International Journal of Climatology*, **34**, 1628-1641, doi:10.1002/joc.3791.

Sahai, A. K. and Pattanaik, D. R., 2018, "Evaluation of Real-Time Extended Range Forecast (ERF) of southwest monsoon, heat wave, cold wave, cyclogenesis and northeast monsoon during 2017", No. ESSO/IMD/NWP- Extended Range Forecast (ERF) Report No. 01 (2018)/05.

Sahai, A. K., Sharmila, S., Abhilash, S., Chattopadhyay, R., Borah, N., Krishna, R. P. M., Joseph, S., Roxy, M., De, S., Pattanaik, S. and Pillai, P. A., 2013, "Simulation and extended range prediction of monsoon intraseasonal oscillations in NCEP CFS/GFS version 2 framework", *Curr. Sci.*, **104**, 10, 1394-1408.

Sarangi, C., Kanawade, Kanawade, V. P., Tripathi, Sachchida N., Thomas, Abinand and Ganguly, Dilip, 2018, "Aerosol-induced intensification of cooling effect of clouds during Indian summer monsoon", *Nature Communications*, **9**, 3754, doi:10.1038/ s41467-018-06015-5.

Sarangi, C., Tripathi, S. N., Kanwade V. P., Koren, I. and Pai, D. S., 2017, "Investigation of the aerosol-cloud-rainfall association over the Indian summer monsoon region", *Atmos. Chem. Phys.*, **17**, 5185-5204, doi:10.5194/acp-17-5185-2017.

Sharma, Kuldeep, Raghavendra, Ashrit, Ebert, Elizabeth, Mitra, Ashish, Bhatla, R., Iyengar, Gopal and Rajagopal, E. N., 2018, "Quantitative precipitation forecasts during the Indian Summer Monsoon", *Journal of Earth System Science*, **128**, 4, https://www.ias.ac.in/public/Volumes/jess/forthcoming/JESS-D-17-00278.pdf.

Sisodiya, A., Pattnaik, S., Baisya, H., Bhat, G. S. and Turner, A. G., 2019, "Simulation of location specific severe thunderstorm events using high resolution land assimilation", *Dynamics of Atmospheres and Oceans*, **87**, https://doi.org/10.1016/j. dynatmoce.2019.101098.

Swapna, P., Jyoti, J., Krishnan, R., Sandeep, N. and Griffies, S. M., 2017, "Multidecadal Weakening of Indian Summer Monsoon Circulation Induces an Increasing Northern Indian Ocean Sea Level", *Geophysical Research Letters*, **44**, 20, 10560-10572, https://doi.org/10.1002/2017GL074706.

Swapna, P., Krishnan, R., Sandeep, N., Prajeesh, A. G., Ayantika, D. C., Manmeet, S. and Vellore, R., 2018, "Long-term climate simulations using the IITM earth system model (IITMESMv2) with focus on the South Asian monsoon", *Journal of Advances in Modeling Earth Systems*, **10**, 5, 1127-1149, https://doi.org/10.1029/2017MS001262.

Swapna, P., Roxy, M. K., Aparna, K., Kulkarni, K., Prajeesh, A. G., Ashok, K., Krishnan, R., Moorthi, S., Kumar, A. and Goswami, B. N, 2015, "The IITM earth system model: Transformation of a seasonal prediction model to a long term climate model", *Bulletin of the American Meteorological Society*, **96**, 1351-1368, https://doi.org/10.1175/ BAMS-D-13-00276.1.

Vinnarasi, R. and Dhanya, C. T., 2016, "Changing characteristics of extreme wet and dry spells of Indian monsoon rainfall", *J. Geophys. Res.*, **121**, 5, 2146-2160, doi: 10.1002/ 2015JD024310.

Yadav, R. K., 2012, "Why is ENSO influencing Indian northeast monsoon in the recent decades?", *Int. J. Climatol.*, **32**, 2163-2180.