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Indian Monsoons Variability and Extreme Weather Events: Recent Improvements in Observations and Modelling

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Preamble

Understanding the variability of the Indian monsoon system is vital as it plays a vital role in the economy and agriculture. The two essential elements of the Indian monsoon are - the summer monsoon or southwest monsoon, during which most of the annual rainfall in India occurs from June to September and the Northeast winter monsoon that brings rainfall to the south-eastern part of India through north-easterlies during October to December. There are many instances of years with a flood (strong monsoon) or drought (weak monsoon) during which India as a whole receives excess or deficient seasonal rainfall, respectively. Indian Summer Monsoon (ISM) variability is highly determined by internal dynamics arising from ocean-atmosphere–land interactions and remote teleconnections via different climate modes (e.g., Goswami and Chakravorty 2017). 49% of employment in India is directly or indirectly involves agriculture and allied sectors. Thus, an advance intimation of monthly and seasonal rainfall will be highly useful and beneficial to the farming community which inturn will strengthen the country's economy.

In addition to the understanding of monsoon variability, particularly for the regional aspects, the heavy rainfall events associated with monsoonal systems also play a vital role in contributing to the annual monsoon rainfall and the country's agriculture economy. Therefore, the monsoonal heavy rainfall systems also need to be understood with the use of observations and modeling. Furthermore, the prediction of high impact weather events is also very much important to the state and central disaster management authorities to reduce the human and cattle loss. It is also essential to understand the land surface feedback and its impact on these extreme weather events also need to be accessed. Therefore, in this report, we have provided brief discussion on recent progress (2016 to 2020) in monsoon modeling, understanding monsoon variability mainly focusing on interannual to decadal variability, monthly and seasonal prediction of monsoon, heavy rainfall associated with monsoon systems and other extreme weather events such as tropical cyclones, severe thunderstorms and above.

Indian Summer Monsoon Variability

Interannual Variability

El Niño-Southern Oscillation and ISM Rainfall

Interannual variability of ISM rainfall is tied to various regional and remote forcings such as sea surface temperature (SST), snow cover, and leading climate models in different parts of the globe (e.g., Ashok *et al*., 2018; Prabhu *et al*., 2016; Chowdary *et al*. 2019). Notably, the El Niño Southern Oscillation (ENSO) in the tropical Pacific oceans know to display the seminal impact on ISM rainfall. Gadgil and Francis (2016) suggested that during El Niño, when the convection

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over the equatorial central Pacific intensifies, there is a high propensity for intensification of convection over the northwest tropical Pacific (NWTP). They stated that El Niño appears to have an impact on the rainfall over the Indian region via its impact on the convection over the West Pacific, particularly over the NWTP region. Analysis from the Paleoclimate Modeling Intercomparison Project 3 (*PMIP3*) *models* by Tejavath *et al*., (2019) showed that the interannual ENSO-Monsoon links have been robust throughout the past millennium, but modulated by the slow changes in the equatorial zonal circulation associated with external changes. Amat and Ashok (2017) explored the association of climate drivers such as ENSO, Modoki and Indian Ocean Dipole (IOD) for local rainfall in various states, and thereby their importance for local Kharif rice production. In the recent past, many studies highlighted the impact of La Niña events on ISM rainfall variability. Aneesh and Sijikumar (2017) suggested that the above normal ISM rainfall events are considerably decreasing during post-1980 La Niña events and the monsoon Low-Level Jet (LLJ) and the upper-level Tropical Easterly Jet (TEJ) showed a noticeable decrease in their core wind speed during post-1980 La Niña years compared to pre-1980. They have attributed these changes to the Indian ocean warming and enhancement of convection over the equatorial region during the post-1980s. Chakraborty *et al*. (2017) highlighted the importance of the delayed impact of winter La Niña on ISM rainfall and suggested the most pronounced reduced precipitation is seen during summer in the western and southern parts of the Indian land region when the preceding winter was La Niña.

Further, the impact of multi-year La Niña events on south Asian summer monsoon rainfall is examined in observations and Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor *et al*. 2012) models by Raj Deepak *et al*., (2019). They reported that during the first year, significant negative rainfall anomalies are seen over most of the ISM region except in the Sundarbans region, and in the case of the second year, positive rainfall anomalies are noted. These changes are mainly associated with changes in local circulation patterns in response to differences in SST anomaly patterns related to La Niña events in the first and second year.

Realistic simulation of large-scale circulation patterns associated with ENSO is vital in coupled models to represent teleconnections to different regions of the globe. The diversity in representing large-scale circulation associated with ENSO-ISM teleconnections in CMIP5 models is examined recently (Ramu *et al*., 2018; Roy *et al*., 2018). Ramu *et al*. (2018) demonstrated that in many models, El Niño induced Tropical Indian Ocean (TIO) SST anomalies are not well represented and warm Pacific SST anomalies associated with El Niño are shifted too far west unlike in the observations. This resulted in poor large-scale circulation patterns and inadequate ENSO-ISM teleconnections in many models. Roy and Kripalani (2019) suggested that observed change in ISM behavior, in the contest of ENSO-Monsoon teleconnections, is influenced by regional Hadley circulation via the North Atlantic Oscillation (NAO) in the northern hemisphere and IOD in the southern hemisphere. They also found that such features are not captured well in models. Analysis of the CMIP model simulations by Azad and Rajeevan (2016) suggested the possibility of having more frequent El Niño events could trigger more droughts over India and maintain a stable inverse relationship between El Niño (developing phase) and ISM rainfall in future. Srivastava *et al*. (2019) suggested that ENSO–monsoon relationship over the ISM region is dependent on the zonal location of the ENSO induced temperature anomalies in the subtropical Afro-Asian region. Previous studies have focused mainly on developing El Niño's influence on ISM rainfall. However, recently Chowdary *et al*. (2017) showed that the variations in decaying El Niño could strongly influence ISM rainfall and circulation. They reported from observations that ISM rainfall is above normal/excess during Early Decay years, normal during Mid Decay years and below normal/deficit in No Decay years, indicating that the differences in El Niño decay phase display profound impact on the ISM rainfall on interannual time scale. Srinivas *et al*., (2019) showed that many CMIP5 models exhibited better skills in simulating differences in decaying El Niño but displayed limited skills in producing teleconnections with ISM rainfall.

Kulkarni *et al*. (2016) noted the importance of El Niño influence in determining the regional rainfall variability. They found that the seasonal rainfall over Marathwada is well correlated with Niño 3.4 SST and droughts over this region likely to be intensified due to El Niño years. Soraisam *et al*. (2018), apart from bringing out the need for better datasets to reduce the uncertainties in studying the climate change and variability of North East India shows that the ENSO events do not have significant impact on the summer monsson rainfall in the region.

The El Niño Modoki/La Niña Modoki

The global impacts of the ENSO Modokis are distinct, be it an impact opposite to that of the canonical events, or a change in the intensity of the impacts. Previous studies reported that the El Niño Modoki impacts cause a deficit in the rainfall stronger for ISM as compared to be that of the canonical El Niños. Recently Ashok *et al*. (2019) suggested that the impact of El Niño Modokis summers is seen to be relatively more prominent in peninsular India, while the impacts of extreme El Niño Modok is such as 2002 and 2004 seem to be more wide-spread. Preethi *et al*., (2019) reported that observations of post-1960s exhibit a declining trend in monsoon rainfall with frequent occurrence and intensification of droughts along with an increase in the percentage of area under moderate and severe drought conditions and are associated with variations in SST over tropics and most likely El Niño Modoki. They also suggested that future projections of all-India drought indices in a couple of models indicate frequent droughts during the near and mid future (2010-2069) concerning the recent historical period.

Atlantic Niño

Some studies suggested that the Atlantic Niño could influence the year to year variability of ISM rainfall through equatorial atmospheric Kelvin waves (Sabeerali *et al*., 2019; Pottapinjara *et al*., 2016) and by modulating the Asian Jet (Yadav *et al*., 2018; Raj Deapik *et al*., 2019). Sabeerali *et al*. (2019) noted a robust increase in the interannual variability of SST over the eastern tropical Atlantic Ocean in recent decades and suggested that an increase in the number of strong Atlantic Zonal Mode (AZM) events toward the end of the twentieth century. They have reported that the increase in strong AZM events alters the large-scale monsoon circulation over the Indian subcontinent by enhancing the Kelvin wave response into the Indian Ocean, leading to an enhanced AZM-ISM rainfall teleconnection. Modulation of the ISM due to Atlantic Niño through the Asian Jet is explored by Yadav *et al*. (2018) as follows. The positive phase of the Atlantic Niño intensifies the inter-tropical convergence zone, as a result of this local tropospheric warming, over the equatorial east Atlantic and West Africa, owing to the enlargement of the upper-troposphere divergence. This provokes meridional stationary waves due to the stronger meridional transfer of energy, as the influences of background jet-streams are minimal over North Africa and Europe. This caused changes in the Asian Jet east of the Caspian Sea, owing to the reduction in the upper-troposphere divergence towards the Indian subcontinent and caused for above (below) normal rainfall over north-east (north-west) India. Pottapinjara *et al*., (2016) reported significant correlations between the ISM rainfall and the low-level zonal winds in the western equatorial Atlantic and heat content in the eastern equatorial Atlantic in the boreal spring season. They suggested that coherent changes in low-level winds and the evolution of the heat content in the deep tropical Atlantic in the boreal spring may have some potential for skillful predictions of the following summer monsoon anomalies, especially during non ENSO years when the predictability of ISM rainfall tends to be low.

Indian Ocean Impacts

In a recent study, the regional asymmetries arising from both phases of IOD teleconnections to India are discussed by Behera and Ratnam (2018). The ISM rainfall variability related to opposite phases of the IOD is investigated by picking eight positive IOD (1982, 1994, 1997, 2003, 2007, 2008, 2012, 2015) and five negative IOD events (1992, 1996, 1998, 2013, 2016) since the satellite era of 1982. They have found that the ISM rainfall response may not necessarily be spatially coherent to both phases of IOD. Yadav and Roxy (2019) noted that in the recent two decades (1996-2017), the north Indian summer monsoon rainfall (NISR) showed a decreasing trend with increased variability, much larger than the earlier period (1979-2000). They have suggested that the warmer SST over the equatorial eastern Indian ocean (EEIO) induce strong convection and associated northward propagating off-equatorial Rossby gyres to the west of EEIO, spreading the tropospheric heating towards the northeast of India, resulting in the observed decreasing trend in the recent decades. Impact of variations in Wyrtki jets on ISM rainfall is studied by Deshpande *et al*. (2018) and they demonstrated that anomalously strong eastward jets accumulate warm water in the eastern equatorial Indian Ocean in early summer, leading to anomalous positive upper ocean heat content and supporting more local convection in the east. This induces subsidence over the Indian landmass and alters monsoon rainfall by modulating monsoon Hadley circulation.

Western North Pacific Impacts

The impact of western north Pacific convection and circulation on ISM is also highlighted in recent years. Surendran *et al*. (2019) suggested that the variability of June all India Rainfall (AIR) is found to have the strongest link with a variation of rainfall over NWTP, with AIR deficit (excess) associated with enhancement (suppression) of NWTP rainfall. They suggested that in years with large rainfall excess/ deficit, the strong link between AIR and NWTP rainfall exists through differences in the Rossby wave phase steered in the subtropical westerly jet. A shift in the mean ISM circulation, with a cyclone-like intensification over northwestern Pacific, is seen in recent decades (e.g., Preethi *et al*., 2016; Feba *et al*., 2017). Feba *et al*. (2017) suggest that such a decadal cyclonic intensification opposes the anomalous anticyclonic signature related to the El Niños, and weakens the impact of the El Niño. Interestingly, this study also finds a simultaneous strengthening of cross-equatorial winds over the equatorial Indian Ocean in recent decades, in apparent association with the weakening of ISM-ENSO links (Feba *et al*., 2018). Recent studies by Srinivas *et al*. (2018) showed that the Pacific-Japan (PJ) pattern also strongly influences the ISM interannual variability. They found that the northwestward propagating Rossby waves, in response to anomalous convection over the Maritime Continent corroborated by low-level convergence in the southern flank of westward extended tropical western North Pacific anticyclone associated with PJ, increase rainfall over southern peninsular India. Furthermore, the north Indian Ocean (NIO) warming induced by easterly wind anomalies along the southern periphery of the tropical WNP-NIO anticyclone enhances local convection, which in turn feeds back to the WNP convection anomalies. Adding to the PJ pattern, Chowdary *et al*. (2019) examined the influence of the Indo-Western Pacific Ocean Capacitor (IPOC) mode on South Asian summer monsoon rainfall variability. They found from the observations that the IPOC mode induces a tripole pattern in precipitation anomalies over the South Asian region with strong positive precipitation anomalies over some parts of Western Ghats and Sundarbans and Bangladesh region separated by negative precipitation anomalies over the monsoon trough region. Their model experiments revealed that the WNP anticyclone influences the rainfall over the monsoon trough region and the Sundarbans-Bangladesh region. Further, the moisture convergence induced by local SST warming is mainly helping to sustain enhanced Western Ghats rainfall.

Mid and Extra-tropics Influence or Teleconnections

It is worth mentioning a recent study that has shed new insights on the phenomenon of mid-tropospheric cyclones (MTC) in the ISM (Choudhury *et al*. 2018). MTCs are a distinct class of synoptic disturbances, characterized by quasi-stationary cyclonic circulation in mid-tropospheric levels, which often produce heavy rainfall and floods over western India around the region of Gujarat during the summer monsoon. Although the importance of MTCs during the summer monsoon was recognized by Indian meteorologists since the 1960s, scientific progress on MTCs has been relatively slow as compared to the Bay of Bengal monsoon low-pressure systems and depressions. By combining TRMM satellite heating observations, reanalysis circulation data, and numerical experiments using a simplified atmospheric model, Choudhury *et al*. (2018) have elucidated the phenomenon of mid-tropospheric cyclogenesis during the Indian summer monsoon. This study showed that the genesis of MTCs is linked to the active phase of the regional-scale poleward-propagating intraseasonal rainbelts and radiative cooling further northward in the dry inland areas of Southwest Asia. Most importantly, this study demonstrated the role of top-heavy latent heating associated with stratiform-type precipitation in mesoscale convective systems on the formation of MTCs over Gujarat and adjoining areas during the summer monsoon season.

In a recent theoritical study, Govardhan *et al*. (2017) talk of the role of break-induced barotropic instability triggering in an active phase through the formation of synoptic disturbance in about 69% of the cases since 1958.

The role of subtropical deserts in the ISM system studied the by perturbing surface albedo over the subtropical deserts using a state-of-the-art coupled model (Sooraj *et al*., 2019). They found that the modulations of the meridional tropospheric temperature gradient along with stronger equatorial asymmetry of mean easterly shear and moisture distribution over the Indian domain are key-factors for explaining the ISM response and its nonlinearity to the albedo perturbations over the Northern Hemisphere subtropical deserts. Sujit *et al*. (2019) suggested that an increase (decrease) in Eurasian snow cover decreases (increases) the atmospheric temperature at high latitudes owing to an increase (decrease) in the surface albedo. They reported that as a result of increase in snow cover, the Equator to Pole temperature gradient increases (decreases) and causes for increase (decrease) in the net poleward energy transport by the atmosphere, affecting the net available energy in the Tropics. These manifest as changes in tropical air-sea interactions, which in turn may affect ISM rainfall.

Further, Prabhu *et al*. (2016) pointed out that excessive wintertime Eurasian snow leads to an anomalous cooling of the overlying atmosphere and is associated with the negative mode of Atlantic Oscillation and cold anomalies over the tropical Atlantic persists up to the following summer leading to an anomalous zonal wave-train further inducing a descending branch over northeast India resulting in weak summer monsoon rainfall. Kakade and Kulkarni (2017) reported that the Arctic-oscillation and ISM rainfall showed a direct concurrent relationship with each other in monsoon season and winter Arctic Oscillation is indirectly influencing ISM rainfall by modulating mid-tropospheric zonal wind anomaly over 60°N-70°N; 5°W-55°W. Recent studies propose that aerosol loadings can influence ISM rainfall (Fadnavis *et al*., 2019) and these can have implications for the ENSO impacts on monsoon (Fadnavis *et al*., 2016). We need more observations and better models to understand the monsoon-ENSO relationship and extraneous factors that influence the relationship.

Multi-decadal to Centennial Variability

Apart from ENSO, the dominant modes in the Pacific, such as the Pacific Decadal Oscillation (PDO) and Inter-decadal Pacific Oscillation (IPO), have a considerable impact on ISM rainfall variability at various time scales (Joshi and Kucharski 2016; Malik *et al*., 2017). Variations in ISM rainfall, characterized by distinct epochs of above and below normal monsoon activity, typically lasting for about three decades. ISM rainfall shows coherent multi-decadal variability with an approximate periodicity of 55-60 years. Using 500 years of different proxies of monsoon rainfall, Goswami *et al*. (2016) suggested that that the Asian monsoon has a multi-decadal oscillation with a period between 50 years and 80 years that change in time in an episodic manner. They noted that existence of high coherence between Asian monsoon multi-decadal mode and that of the *Atlantic Multi-decadal Oscillation* (AMO), ENSO and PDO and suggested that they all are likely to be an integral part of a global multi-decadal mode with a periodicity of 50-80 years.Given the limited data period of reanalyzed and observed datasets, these new findings on the decadal variability associated with slow processes need further verification through redundant analysis with multiple data sets and modeling experiments. From this context, it is relevant to note that a recent analysis of nine PMIP3 simulations for the two dominant epochs of the last millennium, known as the 'Medieval Warm Period' (CE 950-1350) roughly followed the Little Ice Age (CE 1500-1850) suggests that the simulated interannual ISM-ENSO negative correlations are statistically significant in these through regimes, though the ENSO-monsoon relationship waxes and wanes on multi-decadal through decadal time scales (Tejavath *et al*., 2019).

Interestingly, this study also hints that slow background changes in the tropical Pacific can modulate the interannual ENSO-ISM relationship. Ali *et al*. (2019) used combined high-resolution $\delta^{13}C$, total organic carbon (TOC), sediment texture, and environmental magnetic data of the samples from a ~3 m deep glacial outwash sedimentary profile from the Sikkim Himalaya to study ISM variability. From decadal to centennial-scale records, they have identified five positives and three negative excursions of the ISM since last ~13 ka. The most prominent abrupt negative ISM shift was observed during the termination of the Younger Dryas (YD) between ~11.7 and 11.4 ka. While, ISM was stable between ~11 and 6 ka, and declined prominently between 6 and 3 ka. Surprisingly, during both the Medieval Warm

Period (MWP) and Little Ice age (LIA) spans, ISM was active in this part of the Himalaya.

Preethi *et al*. (2017) revealed that the teleconnections between South and East Asian monsoon rainfall also exhibit a multi-decadal variation with alternate epochs of strengthening and weakening the relationship. Chakravorty *et al*. (2016) found that ISM rainfall anomalies during El Niño developing summer in epoch-1 (1950-1979) are mainly driven by El Niño forcing throughout the season, whereas TIO SST exhibits only a passive influence. On the other hand, in epoch-2 (1980-2009), ISM rainfall does not show any significant relation with the Pacific during the onset phase of monsoon, whereas the withdrawal phase is strongly influenced by El Niño. Further, how local ocean-atmosphere interactions, remote air-sea interactions, and teleconnections with multi-decadal ENSO and AMO result in the multi-decadal monsoon mode is proposed by Goswami and Chakravorty (2017). Josepth *et al*. (2016) noted that the during dry epochs of ISM rainfall, when frequent drought monsoons, north moving Bay of Bengal severe cyclones occurred and are incoherent with a cold phase of AMO. Nagaraju *et al*. (2018) investigated the remote influence of AMO in modulating the inter-decadal relationship between ISM rainfall and the Australian Summer Monsoon Rainfall. They found that during the 1932-1966 (sub-period II), the low-level westerlies were stronger than the sub-periods of 1903-1931 (sub-period I) and 1967-1992 (sub-period III). The stronger westerly anomalies apparently resulted in a low-level convergence, opposing the easterly wind anomalies associated with the El Niño and reduced the El Niño-associated negative rainfall anomalies over northern Australia, leading to the ASMR-ENSO association fall below the statistical significance.

North-East Monsoon

Sreekala *et al*. (2018) examined the combined effect of MJO, ENSO, and IOD on the intraseasonal and interannual variability of northeast monsoon rainfall over south peninsular India. They revealed that the intraseasonal variation of daily rainfall over south peninsular India during NEM season is associated with various phases of eastward propagating MJO life cycle and which as a strong impact on interannual variability of NEM. Nageswararao *et al*. (2019) found that the promising relationship of various NEM rainfall events and its associated rainfall with ENSO and IOD have weakened in the recent decades after 1988. On the other hand, Sanap *et al*. (2019) noted from observations that Easterly waves (EW) over NIO play a seminal role in the occurrence of heavy rainfall events over south-eastern peninsular India during NEM season. They reported that EW activity found to be weak during La Niña and neutral years and significant warming of tropical Indian Ocean and easterly flow during El Niño years are the main contributing factors for initiation and westwards propagation of EWs. Singh *et al*. (2017) pointed out that despite having strong warming in the central and eastern Pacific associated with El Niño, NEM rainfall variations over southern peninsular India is mostly determined by SST gradient over the Indo-western Pacific region and number of systems formation in the Bay of Bengal and their landfall. Prasanna *et al*. (2019) examined the variability of NEM rainfall over southern Peninsular India associated with multiyear-La Niña events. Analysis of observations showed that despite noticeable weakening in the equatorial Pacific cooling from the first year to the second year, strong La Niña teleconnections and the rainfall deficiency over the southern peninsular India region remains the same in most of the multiyear-La Niña events (70%). Boyaj *et al*. (2017) showed that the extremity of the Chennai rainfall is contributed to by the concurrent extreme El Niño of 2015 as well as the increasing warming in the Bay of Bengal off the coast of Tamil Nadu. This warming is also supposed to be leading to more TCs. Mishra *et al*. (2019) have used a multiproxy approach (geochemistry, clay mineralogy and end-member mixing analyses of the grain size parameters) on the radiocarbon-dated sediment profile from Ennamangalam Lake, southern India to reconstruct the past moisture sources in the region and studied climate variability associated with NEM and ISM rainfall. Their analysis suggested that the presence of an inverse relationship between the south-west and the north-east monsoon strength during the late Holocene affected by the increasing ENSO variability.

Winter Monsoon: North-west India

Over the northern Indian region, almost one-third of annual precipitation is received during winter (December, January, and February) by eastward-moving extratropical cyclone called western disturbances (WDs) in Indian meteorological parlance. Dimri *et al*. (2016) studied winter time dynamics associated with large-scale flows and WDs influencing winter precipitation. They have highlighted the importance of ENSO, Walker circulation, Hadley circulation, subtropical westerly jet in determining the winter monsoon precipitation. Midhuna and Dimri (2018) suggested that in the positive phase of Arctic Oscillations years, polar and/or extratropical mass moves southwards and mid-latitude interactions lead to enhanced precipitation over Indian winter monsoon regions. Singh *et al.* (2019) examined the impacts of the approaching active WDs on local-scale meteorological variables utilizing *in situ* observations over the north-west Himalayan (NWH). They suggested that approaching active WDs is found to cause a drop in maximum air temperature, ambient air temperature, surface atmospheric pressure and sunshine duration whereas a rise in the minimum air temperature and relative humidity in the 24-hr time interval over the NWH region.

Model Developments and Modelling Studies of Monsoonal Systems

The last few decades have witnessed impressive advances in numerical modeling and prediction of weather and climate (Stocker, 2013, Bauer *et al.* 2015). In particular, substantial improvements in the skill of short and medium-range weather forecasts have been realized in extra-tropical regions (Bauer *et al.* 2015). Progress in tropical and monsoon predictions has evolved at a relatively slower pace given the inherent complexities in numerical modeling of tropical processes which are dominated by interactions among atmospheric circulation, moisture, precipitation, clouds, organized convection, radiation, aerosols, ocean-land-atmospheric feedbacks on different space and time scales (e.g., Houze, 1997, Stevens and Feingold, 2009, Krishnamurti *et al*. 2010, Wheeler *et al*. 2016, Vitart *et al*. 2017).

Numerical modeling of ISM and its variability across different scales has attracted researchers worldwide over the last several decades. A summary of monsoon simulation studies from the 1960s until 2011 can be found in Krishnan *et al*. (2011). The last 9-10 years have seen significant progress from India in terms of advancing the skill of monsoon dynamical forecasts on short-range, medium-range, extended-range and seasonal scales (e.g., Mukhopadhyay *et al*. 2019, Abhilash *et al*. 2013a, 2013b, 2014, Ramu *et al*. 2016; Hazra *et al*. 2017; Saha *et al*. 2019; Krishna *et al*. 2019). In particular, the Monsoon Mission project of the Ministry of Earth Sciences, Govt of India showed that focused and concerted efforts in model development for improving monsoon prediction can significantly contribute in the improvement of CFSv2 model physical parameterization and subsequently to the improvement of model fidelity in capturing the mean and intraseasonal variability of Indian summer monsoon (Ganai *et al*. 2019, Abhik *et al*. 2017, Ganai *et al*. 2015, 2016).

A Summary of S2S and Seasonal Forecasting

The seasonal to sub-seasonal forecast remains a challenge to the numerical modelers. Significant improvements in subseasonal forecast of up to 2 to 3 weeks have been achieved through the development of extended-range forecast based in GFS and CFS grand ensemble. In this suite of models, the GFS has been run with the bias-corrected SST predicted from CFSv2 (Abhilash *et al*. 2013c). The extended range prediction system developed by IITM and later operationalized by IMD has yielded a significant impact on the prediction of active and break phases of monsoon which is highly beneficial for the agriculture sector. The extended range forecast has also been extended to provide cyclogenesis guidance over Indian oceans (Ganesh *et al*. 2018). The extended range forecast of 2 to 3 weeks has also been found to be useful in drought monitoring in the country during monsoon season. Another critical aspect of the extended range forecast is the heatwave and cold wave episode. The skill of the model in predicting anomalously strong heat and cold waves in the country is found to improve the operational forecast skill in the country (Mandal *et al*. 2019). Developing the seasonal dynamical prediction based on CFSv2 was one of the key objectives of the Monsoon Mission program of the Ministry of Earth Sciences, Government of India. Under this program, the NCEP CFSv2 model was adopted. Significant indigenous as well as through extramural collaborative efforts, improvement in CFSv2 model physics (Pokherel *et al*. 2018, Abhik *et al*. 2017, Hazra *et al*. 2017). A new stochastic multi-cloud parameterization (Goswami *et al*. 2017a, 2017b, 2017c) has been implemented in

CFSv2 to address the stochastic nature of evolution of clouds within GCM grids and this development has shown significant improvement of systematic bias of CFSv2 for the seasonal mean and intraseasonal variability of rainfall and also improved the intraseasonal convectively coupled tropical waves. The highest resolution (~CFSv2T382~38 km) has been found to provide reasonable monsoon prediction skills (~0.55) for JJAS monsoon precipitation.

It has been shown by (Tirkey *et al*., 2019, Malviya *et al*., 2018) that a mere increase of resolutions does not improve the model fidelity in simulating ISM. Tirkey *et al*. used three resolutions of CFSv2, namely T62 (horizontal resolution ~200 km), T126 (~100km) and T382 (~38km) to evaluate model skill in simulating intraseasonal monsoon oscillations (MISOs). It is concluded that the increase of model resolution could not improve the representation of moist processes and thereby, the impact of resolution is hardly seen in improving the model fidelity. However, systematic improvement of cloud and convection parameterization has developed the model performance in lower and higher resolution as shown by Ganai *et al*. (2019). Ganai *et al*. (2019) modified the fractional cloud condensate in the revised SAS (simplified Arakawa Schubert) scheme, which has enabled the model to reduce unrealistic convective rain and eventually improve the large scale (stratiform) rain. This modification is shown to strengthen the CFSV2 model seamlessly at T126 resolution and the very high-resolution GFS model at T1534 (~12.5 km) to improve the performance extreme precipitation event. The GFS T1534 with the modified convection shows better skills in capturing the heavy rainfall event over Mumbai. It is also noted that improvement of cloud and convective parameterizations enhances the skill (correlation and intraseasonal variance) of the lower resolution CFSv2 T126 as good as that of CFSv2 T382 showing the improvement of mean and intraseasonal variability of monsoon (Rao *et al.* 2019). India has taken a quantum jump in establishing the highest resolution (12.5 km) short range ensemble forecasting system globally with 21 ensemble members for ten days forecast. This ensemble prediction system (GEFS at 12.5km) has enabled to initiate much-needed block-level agriculture forecasting system, river basin probabilistic forecast system on experimental basis over the country. The establishment of a 12.5 km ensemble prediction system shows very good skill in forecasting tropical cyclones (namely “FANI”) and its strike probability with longer forecast lead time. The GFS/GEFS forecast system has also been useful in predicting extreme precipitation events with 3 to 4 days lead time.

Monsoon Response to Climate Change: Earth System Model Development

Substantial progress in climate and monsoon modeling during the last few years has been the development of the IITM Earth System Model (IITM ESM) for studying long-term climate variability and change. The IITM ESM was developed at the Centre for Climate Change Research (CCCR), IITM, Pune, by transforming the CFSv2 operational seasonal prediction model into a long-term climate model suitable for investigating climate change-related scientific issues (Swapna *et al*. 2018, Krishnan *et al*. 2019a). The latest IITM ESM (version 2) is a radiatively balanced climate modeling framework for studying climate change, as well as the response of global and regional climate including the monsoon hydrological cycle to anthropogenic forcing (e.g., Greenhouse gases (GHG), aerosols, land-use/land-cover changes, etc.). The following are some of the key elements incorporated in the IITM-ESMv2: A realistic representation of Arctic sea-ice distribution, Atlantic meridional overturning circulation (AMOC) – a large-scale oceanic circulation which has significant relevance to the Earth’s climate, a good representation of the ISM precipitation and circulation, capabilities to investigate the impacts of aerosol forcing (natural-dust, sea-salt, volcanoes; and anthropogenic–sulfate, nitrate, organic carbon, black carbon, etc.), and land-use land-cover changes on the climate and the monsoon in particular (Swapna *et al*. 2018, Krishnan *et al*. 2019a). The IITM-ESMv2 is the first climate model from India to contribute to the Coupled Modeling Intercomparison Programme (CMIP) – Phase 6 (CMIP6) and the upcoming Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). For this purpose, several long-term climate simulations have been performed following the CMIP6 protocols and the CMIP6 model outputs from the IITM-ESM are currently being made available to the National and Global research community required for climate change impact assessments. Besides, various numerical simulation experiments using the IITM-

ESMv2 are currently in progress for the detection, attribution and future projections of climate change and the associated changes in the Indian monsoon, climate and weather extremes.

In addition to the IITM-ESM simulations, high-resolution atmospheric-only model experiments were performed at CCCR-IITM to understand the observed changes in the Indian monsoon precipitation during the last 5-6 decades (Krishnan *et al.* 2016). This model setup has high-resolution telescopic zooming (grid size < 35 km) over South Asia, which is useful for better resolving orographic gradients, regional vegetation, land use/land cover changes and aerosol forcing. An important scientific finding from these experiments showed that the combined effects of anthropogenic aerosol-forcing, regional land-use changes and the rapid warming trend of the equatorial Indian Ocean have significantly influenced the observed weakening trend of monsoon precipitation since the 1950s. Besides, the high-resolution model experiments demonstrated that a weakening trend of monsoonal circulation in a warming world could significantly enhance the occurrence of localized intense precipitation events (intensity > 10 cm day^{-1}) over central India during the rainy monsoon season (Krishnan *et al.* 2016). Another recent climate modeling study provides robust evidence for the role of climate change and accelerated warming of the Tibetan Plateau in altering the background winter-time subtropical westerlies, to favor enhanced amplitude variations of the synoptic-scale western disturbance activity and associated heavy wintertime precipitation occurrences over the western Himalayas during the recent few decades (Krishnan *et al.* 2019b).

Extended Range Prediction of Indian Summer Monsoon Rainfall

The complexity of ISM has been a challenge for the scientific community over the past few decades due to the complexities involved with it as well as the demand for a reliable forecast. Complexities are in the form of land surface heterogeneities, mesoscale convective activities, and its interaction with the large-scale flow, intranasal variability etc. History of summer monsoon rainfall forecast can be dated back to the late nineteenth century. Extensive studies and forecasting kick-started mainly during the early 1990s. Prediction of ISM rainfall, as well as other parameters, has drastically improved especially over the past two decades. This section discusses some of the recent developments in the extended range prediction of the Indian summer monsoon.

Contemporary methods that have been implemented successfully for the extended range prediction of following the principle of statistical and dynamical methods. Statistical methods use regression analysis and other improvised statistical methods to form an empirical model through a relationship between the predictor and predicted, whereas the dynamical models follow the method of representing the time-varying physical processes of the atmosphere using complex mathematical equations. Several studies have been conducted with both the above-stated methods to improve the understanding and representation of the atmospheric processes, thereby helping in improving the predictive skill of the model. Model developmental activities continue till date, aimed at enhancing the predictive skill of the respective models (Mohanty *et al*., 2019; Pokhrel *et al*., 2018).

Mohanty *et al*. (2019) applied comprehensive statistical methods such as multivariate regression technique based on a singular value decomposition method, principal component regression analysis, and canonical correlation analysis to multi-model outputs. These methods helped build the statistical model for the Extended Range Prediction System (ERFS). Bias corrected general circulation models (GCMs) (Singh *et al*., 2017) outputs are used in the individual statistical approaches and then employed a robust technique to generate a single consensus forecast and all techniques starting from the bias correction to the single forecast altogether formed the ERFS model; and the robustness of the skill of ERFS model is proven (Mohanty *et al*., 2019) for the ISM prediction at met-subdivision level. The above-stated methods yielded high success rates, especially for the monthly forecast of June and July months over the forecast period on a real-time basis between 2011 and 2018. More than 70% of the met-subdivisions had the confidence of more than 60% for the monthly and seasonal rainfall, which was even higher for June and July months. Besides the above-stated methods, experiments were also carried out using other methods such as the neuro-computing approach using SST anomaly, artificial neural network (Niar *et al*., 2018) and weighted multi-model ensemble technique which was found to have a significant impact on the prediction of rainfall using a statistical model.

The ERFS has also been used with success rates for various meteorological applications at the sub-divisional level. Rainfall forecasts from the ERFS have been used in the agricultural model (DSSAT) to generate crop yields for the monsoon season. The forecast of the ERFS was disaggregated into daily sequences, which is a necessity of the crop models. The disaggregated ERFS products are being highly helpful in generating the crop yield forecast (Dhekale *et al*., 2017; Singh *et al*., 2018). Possessing a useful skill, the application of the ERFS in crop yield prediction can help generate agro-met advisories which can be highly beneficial for the end-users. Statistical models are also being used at India Meteorological Department (IMD) on an operational basis using the IMD-SEFS (Statistical Ensemble Forecasting System) using the GCM outputs from various agencies. The statistical models are used for the medium as well as seasonal scale prediction. The IMD-SEFS has comparative skill in simulating the seasonal rainfall at the met-subdivisional level and the rainfall over homogenous regions has quite skill on a seasonal scale. Pattanaik *et al*. (2017, 2019) have concluded that the operational extended-range forecast at IMD has evolved and the current dynamical model (CFSv2), as well as the hybrid (dynamical-empirical) model at IMD using MME, has a better performance in capturing the mean seasonal rainfall, intrapersonal variability, onset of monsoon as well as active and break phases during the summer monsoon season.

Another method that has been highly researched, developed, and applied for the extended range predictions is the dynamical method. Intense research over the past few decades has led to the development of a robust platform in the form of the dynamical weather prediction method. GCMs have been implemented and are highly relied upon by a vast end-user community spreading over agriculture, aerospace, insurance, tourism, hydrology, mining, etc. The seasonal forecast by GCMs presents an overall picture of the atmospheric conditions over a few months. Indian Institute of Tropical Meteorology (IITM) issues seasonal forecast using an improvised GCM, Climate Forecast System version 2 (CFSv2) which has achieved a good skill through various model developmental activities over the past few years (Ramu *et al*., 2016; Pradhan *et al*., 2017; Srivastava *et al*., 2017; Hazra *et al*., 2017). Though most of the atmospheric parameters are quite well represented in a GCM, the primary concern lies with the simulation of rainfall (Chattopadhay *et al*., 2015; Pillai *et al*., 2018). The improvements in the representation of atmospheric processes have helped IITM to achieve a skill of 0.63 (Pokhrel at al., 2018). On an extended range time scale, the mean rainfall amount and pattern are reproduced by the modern-day GCMs (Sahai *et al*. 2015; Chattopadhay *et al*., 2017). GCMs are also quite helpful in representing the mean atmospheric features over the tropics which is extremely important for the global climate (Chattopadhaya *et al*., 2015; Rao *et al*., 2019). The complex processes such as the ENSO, EQUINOO are gaining better predictive skills with the modern-day GCMs which can further be used by a hybrid dynamical-statistical model to yield better forecast results. High-resolution, medium-range forecasting is also being undertaken at the IMD, where the GFS is integrated at T1534 and T574 spectral resolutions. Sridevi *et al*. (2019) showed that the GFS at high resolution was able to provide a more realistic spatial distribution of mean seasonal rainfall. The model is quite skillful in capturing the rainfall 24 hrs in advance.

The National Centre for Medium-Range Weather Forecasting (NCMRWF) used a coupled model for medium-range forecast during monsoon season known as the NCMRWF Unified Model (NCUM) at convection-permitting scales and concluded that the rainfall was simulated quite realistic in the 2-week simulations. The NCUM has identified several extreme rainfall events during the summer monsoon season (Satyanarayana and Kar 2016). The model has a good skill for a lead of 2-4 days, but the skill deteriorates with the increase of lead time to predict the heavy rainfall events during the monsoon seasons. Similar studies by Kar *et al*. (2019) showed that the NCUM has a long spin-up time of 2-4 days while being used for the medium-range forecast. Thus, the model loses mass as the forecast day increases from day 1 to day 10. Sharma *et al*. (2018) evaluated the quantitative rainfall forecast using the NCUM model using the Contiguous Rain Area (CRA) analysis and concluded that the model possesses good skill for a rainfall threshold value of 10 mm/day while it had poor skill for rainfall more than 20 mm/day at a lead of 2-4 days.

GCMs, possess their own systematic biases arising due to the coarser resolution at which GCMs are run, representation of land surface and internal dynamics. A method for filtering out the errors arising due to these problems by the use of the process dynamical downscaling. Dynamical downscaling can also be seen as nesting with a GCM where the GCM outputs are used as the initial and boundary conditions at the boundaries of a regional climate model (RCM). For the prediction of ISM, research activities following the method of dynamical downscaling have helped in reducing the errors in rainfall as well as improving the pattern of simulated rainfall over a particular domain. Using model forecast as well as reanalysis data sets, studies have shown that the rainfall forecast is represented better spatially as well as the skill of rainfall can be elevated by the use of an RCM. The sensitivity of the regional climate model to cumulus schemes, land surface schemes, and moisture convergence schemes present the complex atmospheric conditions parameters that influence the simulation of rainfall significantly (Maurya *et al*., 2017, 2018, Mohanty *et al*., 2019, Sinha *et al*., 2018). They have shown a subsequent improvement in the skill of the regional climate model RegCM in simulating the mean summer monsoon rainfall with the optimization one-by-one of physical processes for the region of interest.

The quest as well the demand for a skillful forecast of the summer monsoon rainfall on a seasonal scale has led to many studies that conclude that the simulation of rainfall requires a unique approach as well representation of micro-scale parameters. Extensive research on various methods has helped in improving the simulation of rainfall over the past decade and making the forecast reliable. The flaws in a particular approach can be solved using another method, and hence the development of a hybrid dynamical-statistical prediction tool may help in providing forecast at smaller scales or the district level and thus be helpful for use by different sectors of the country.

Modeling Studies of Heavy Rainfall Associated with Monsoon

Heavy rainfall generally occurs spatially over a small region and for a short duration of time but causes excess rainfall more than its normal climatological value. Landslides, flash floods, and crop damages associated with extreme rainfall events have major impacts on society, the economy, and the environment. The losses due to extreme rainfall and floods in India are about $3 billion per year, which is 10% of the global economic loss (Roxy *et al*., 2017). There are lots of studies on both observation and modeling of heavy rainfall events all over India.

There is a threefold increase in widespread extreme rain events over central India during 1950-2015, and this is due to an increasing variability of the low-level westerlies over the Arabian Sea (Roxy *et al*., 2017). During the summer monsoon season, river basins located in the central parts of India show a significant increase in the area covered by the heavy rainfall episodes and their intensity (Despande *et al*., 2016). Analysis of dynamical features of heavy rainfall event (June 14-17, 2013) over Uttarakhand reveals that the interplay between the movement of monsoon low along the monsoon trough resulting in strong low-level convergence and constant feeding of moisture from the Arabian Sea resulted in the heavy rainfall event (Ranalkar *et al*., 2016). Analysis of characteristics of rainfall extremes during the southwest monsoon over the northeast Indian region suggests that the highest number of extreme rain events is found in July, followed by June and August. There is a significant decrease in low rainfall events and a significant increase in very heavy (>95 percentile) to extremely heavy (>99 percentile) rainfall events (Varikoden and Ravadekar 2019). Events of moderate and heavy rainfall are increasing during the withdrawal period of Indian summer monsoon over the Indo-Gangetic Plain (Bhatla *et al*., 2019). An increase in the frequency of extreme rainfall events is seen over Konkan & Goa, Madhya Maharashtra, Jammu and Kashmir, central Northeast India (CNEI) and west-central India (WCI) in the recent years (25 years) compared to previous nine decades (Prathipat and Konatham 2019). The seasonal rainfall has increased over Tamil Nadu, Rayalaseema, as well as South Peninsular India because of an increase in the number of high-intensity rainfall events concerning the earlier period (1901-1958), while it has decreased over the other sub-divisions (Nageswararao *et al*., 2019). There is a significant increasing trend in annual rainfall, consecutive wet days and number of days with rainfall > 20 mm; while a decreasing trend of consecutive dry days over the Delhi region (Manikandan *et al*., 2018). Analysis of flood over southeast peninsular India during 2015 northeast monsoon season suggests that easterly wave activity over the Indian Ocean plays a seminal role in the occurrence of the heavy rainfall events during positive phase of the ENSO, while it is found to be weak during negative and neutral phase (Sanap *et al*., 2019). Easterly waves are one of the rain-bearing systems of the northeast monsoon and create floods in the absence of tropical cyclones over south India (Suneetha *et al*., 2018). Analysis of mechanism in occurrence of intense heavy rainfall events suggest that the confluence of moisture-laden winds from East-West shear zone with upper air cyclonic circulations extending up to mid-tropospheric levels located at west-central Bay of Bengal, west Arabian Sea and anti-cyclonic circulation over east-central Arabian Sea lead to the occurrence of intense heavy rainfall events over North Konkan (Sanap *et al*., 2018). During the 1901-to-2013 summer monsoon period, frequency of very light, light and moderate rainy days persists with the almost constant trend, whereas the heavy, very heavy and extreme rainy days exhibit an increasing trend over Odisha (Swain *et al*., 2018). The rate of increase in rainfall amount and number of wet-day are higher in southern Odisha than northern Odisha, which implies that the climate is becoming drier as one moves from south to north and the gradient is also increasing with time (Swain *et al*., 2019b). Analysis of extreme rainfall events over Odisha and dominant large-scale parameters suggests that the Indian Ocean is warmer during extreme rainfall events compared to the dry events, particularly near the seashore of Odisha and the monsoon trough has been shifted south (north) from its normal position during extreme rainfall (dry) events (Swain *et al*., 2019c). Analysis of satellite data (1998-2015) over Central India suggests that heavy rainfall (>60 mm/day) is associated with cold cloud tops (Tb >220K) while moderate rainfall (<60 mm/day and >20 mm) occurs mostly with middle clouds (Tb >220K and > 245K) (Mishra 2019). There are differences in displaying extreme precipitation statistics over the Asian domain among the 20 Coupled Model Intercomparison Project Phase 5 model data outputs, such as high-resolution models simulate maximum intensity of extreme precipitation over the Indian sub-continent, medium-resolution models over northeast India and South China and the low-resolution models over Bangladesh (Kim *et al*., 2019). With the help of an integrated water vapor transport detection algorithm, 364 strong moisture transport events (SMTs) have been identified over the Arabian Sea and these SMTs are responsible for the occurrence of heavy precipitation events and floods over Indian subcontinent during the summer monsoon (Lakshmi *et al*., 2019).

Incorporation of High-Resolution Land Data Assimilation (HRLDAS) based soil moisture and temperature fields in Weather Research and Forecasting (WRF) modeling system suggest better representation of a very heavy rainfall event over Uttarakhand compared to control WRF run (without land data assimilation) (Rajesh *et al*., 2016). Simulation of heavy rainfall associated with monsoon depressions (MDs) over Odisha using the WRF model depicts that the location of the formation of MDs is always behind the actual position of the system and also do the landfall after the actual time. The model is showing higher Heidke skill for less intensity rainfall threshold values (Swain *et al*., 2019a). National Center for Environmental Prediction (NCEP, USA) Climate Forecast System (CFS) version 2 models at two different horizontal resolutions (CFST126 and CFST382) captures intensity and frequency of extreme precipitation events differently. CFST126 free run gives better estimates of the frequency of rainfall events compared to CFST382 and CFST382 free run gives better estimates of the intensity of rainfall events compared to CFST126 (Chattopadhyay *et al*., 2019). Global forecasting system (GFS) model running at India Meteorological Department (T574 and T1534) shows good statistical skill in capturing the 24h accumulated rainfall over climatologically heavy rainfall regions and useful for all parts of the country except for high terrain regions in India (Sridevi *et al*., 2019). The model simulation indicates that the revised, simplified Arakawa-Schubert convection scheme with modified fractional conversion parameter (it has the form of an exponential function of temperature above the freezing level and it is kept constant below the freezing level) shows better fidelity in capturing the mean monsoon features over the Indian Summer Monsoon region (Ganai *et al*., 2019). Among four non-stationary generalized extreme value models, the one that modeled the location parameters as a function of local factors, urban factors, suburban factors, and Pacific Decadal Oscillation exhibits that the urban expansion could increase the magnitudes of extreme precipitation and its recurrence levels under different return periods (Lu *et al*., 2019). Two out of four ensemble members of WRF model corresponding Kain-Fritsch cumulus scheme simulate the extreme rainfall events (cloudburst over Pithoragarh district of Uttarakhand: July 1, 2016) close to the observation and it is also noted that the spread amongst the ensemble members is very large in case of BMJ, AS, MSKF, Tiedke, GF and new Tiedke schemes (Budakoti *et al*., 2019).

Advancements in the Prediction of Extreme Weather Events

Customization of a High-resolution Mesoscale Modeling System for TC Prediction

In this global warming era, extreme weather events (Tropical Cyclones, Monsoonal heavy rainfall, and Severe convection activities etc.) forecast is a very challenging and demanding task for both the operational and research meteorologists. Tropical Cyclones (TCs) over the North Indian Ocean (NIO) region have always caught the attention of all the people from various streams because of their destructive nature and can cause significant loss of lives and property when making landfall due to strong winds, torrential rainfall, and powerful storm surges. Compared to the other basins, the NIO basin, comprised of Bay of Bengal (BoB) and Arabian Sea (AS) is small in area, but highly vulnerable to TCs and associated storm surges due to its conical shape, bathymetry and low lying areas. Of the 23 recorded deadliest storms, 20 are reported in the NIO region (WMO report 2011). So, TCs play a crucial role in the county's growth and the economy.

In recent years, various numerical weather prediction models are operating in real-time to provide the forecast for the TCs over India. As IIT Bhubaneswar is the active partner in Forecast Demonstration Project TC (FDP-TC), the computational R&D laboratory [Weather and Climate systems] lead by Prof. U C Mohanty is providing real-time guidance of the TCs by using high resolution coupled mesoscale model. The real-time continuous model guidance is disseminated to India Meteorological Department (IMD), New Delhi and Bhubaneswar. The success story of IIT Bhubaneswar has also appeared in various international journals (Mohanty *et al*., 2015 and Nadimpalli *et al*., 2016. Osuri *et al*., 2017a). The very severe cyclonic storm (VSCS) "Phailin (2013)" was the strongest cyclone that hit the eastern coast of the India Odisha state since the super cyclone of 1999. But the same story of casualties was not repeated as that of 1999, where approximately 10,000 fatalities were reported. In the case of Phailin, a record 1 million people were evacuated across 18,000 villages in both Odisha and Andhra Pradesh states to coastal shelters following the improved operational forecast guidance that benefited from highly skillful and accurate numerical model guidance for the movement, intensity, rainfall, and storm surge. The same success story was repeated in the case of VSCS Hudhud (2014) that hit the coastal megacity Visakhapatnam and VSCS Fani (2019) that strike Odisha's triplet cities (Cuttack, Bhubaneswar and Puri). This success is mainly due to the immense R&D efforts in improving predictions of TCs using cyclone specific mesoscale modeling system HWRF (Nadimpalli *et al*., 2019).

Further, the sudden change in movements is investigated and the role of steering currents along with vortex scale features explained by Battacharya *et al*., 2015 and Nadimpalli *et al*., 2019. It is also evident that the associated storm surges can cause more casualties when compared to the direct impact of TCs. So, the high population density along the coastal stretch demands a dedicated operational storm surge warning system to predict and evaluate risk due to approaching storms and for the issuance of guidance to the coastal community. Hence, the real-time forecast of the surge height prediction system also uses at IIT Bhubaneswar. The one-way dynamically coupled storm surge model guidance is provided in real-time to IMD for the official forecast (Mohanty *et al*., 2015 and Nadimpalli *et al*., 2016).

Development of Coupled HYCOM- HWRF Modeling System for TC Predictions

With all these above mentioned TC prediction accomplishments, the accurate intensity (pressure drop at the storm center and maximum sustained wind speed) prediction, however, could not be achieved over this basin. Accurate intensity prediction is a vital aspect of the advanced forecast as the disaster mitigation strategies, and precautionary action plans are highly dependent on it. The lag in intensity prediction might be due to not inclusion of ocean impact while predicting the TCs. To investigate the ocean impact on TC track and intensity prediction, real-time SST is updated daily to the only-atmospheric model (Mohanty *et al*., 2019). This shows there is a significant improvement in the intensity prediction considering the ocean impact on the TCs which demanded TC prediction with a high resolution coupled ocean-atmosphere modeling system. TCS, Okchi, Pethei and Fani were predicted with the ocean-atmosphere coupled modeling system hence developed and produced remarkably improved intensity forecast. More statistical analysis with a greater sample size is required to develop confidence in the coupled ocean-atmosphere modeling system.

The improved skill in the forecast ultimately has drawn attention from the Government of India to a capacity-building when faced with a hydro-meteorological disaster. This helps the national and state disaster management authorities to make the best dissemination and decision support system for better adaptation and mitigation policies.

Recent Advancement of Land-atmosphere Feedback Processes Over India

Indian region is characterized by diverse land surface conditions due to its complex topography, soil and vegetation and rainfall distribution. The heterogeneity in surface condition favors the initiation of convective storms and influences various weather events such as thunderstorms, monsoons, heavy rain events and tropical cyclones. The soil moisture is one of the key parameters that control the surface energy and water balance. The land surface evaporation allows transport of surface water from land surface to the atmosphere and part of which converts into a cloud and returns to the surface by rainfall. For such coupling, the Indian region has been identified as one of the soil moisture and rainfall coupling hotspots in the world (Koster *et al*., 2004).

There have been several studies demonstrating the importance of land surface processes on weather and climate systems over India (Osuri *et al*., 2017; Unnikrishnan *et al*., 2017; Nayak *et al*., 2018). Unnikrishnan *et al*. (2017) examined the role of land-atmosphere coupling strength on the South Asian monsoon region and found that SM makes a significant contribution to monsoon rainfall variability and is strongly coupled to the sensible heat flux over the Indian monsoon region. Baisya *et al*. (2017) found positive S-P feedback processes associated with Indian monsoon depression through control on evapotranspiration and moisture flux convergence. Paul *et al*. 2016 demonstrated that the weakening of Indian summer monsoon rainfall due to land use land cover changes through a decrease in evapotranspiration and subsequent decrease in the recycled component of precipitation. The LULC changes and feedbacks should be an integral component of short, medium, and long-range predictions over the IMR (Niyogi *et al*., 2018). Singh *et al*. (2016) found that the significant non-stationarity in ISMR extremes in urbanizing/developing-urban areas (transitioning from rural to urban), compared to wholly urbanized or rural areas. Devanand *et al*. (2018) demonstrated that improved representation of land characteristics in a regional coupled atmospheric-land model improves not only the land atmosphere interactions but also the moisture contributions from distant oceanic sources. The study suggests that the realistic representation of unmanaged irrigation and paddy cultivation over north-northwest India leads to an increase in the late-season terrestrial monsoon precipitation and intensification of widespread extreme events over Central India (Devanand *et al*., 2019). Osuri *et al*. (2017) demonstrated that the realistic SM/ST initialization improves mass flux, convective updrafts and diabatic heating in the boundary layer that contributed to low level positive potential vorticity and thereby improved initiation, movement and timing of severe thunderstorms. The high-resolutions SM and ST initialization has improved the simulation of Uttarakhand heavy rainfall event (Rajesh *et al*., 2016).

Land surface observations, however, are generally available at very few location locations. This constraint the representation of spatiotemporal surface variability and the associated predictability of weather and climate models. Prior efforts have therefore created analysis fields, but they are inadequate for representing small scale and local changes that are important for various convective driven storms. This reinforces to create high-resolution surface conditions over India. Recently, Nayak *et al*. (2018) has developed high-resolution (4 km and

3hourly) soil moisture and soil temperature (SM/ST) dataset surface (0-10 cm) and subsurface (10-40 cm, 40-100cm, 100-200 cm) soil layers for the Indian monsoon region using a Land Data Assimilation System (LDAS). Initially, they have generated this land surface data set for 14 years (2001-2014) and,after that, expanded for 38 years (1981-2018). The high-resolution SM/ST data product proven its credibility through validation with both direct and indirect observations. Long-term LDAS products replicated the diurnal variation, and the seasonal and the inter-annual variability of SM/ST. The utilization of SM/ST in initializing the Weather Research and Forecasting (ARW) model improved the simulation of heavy rainfall associated with monsoon depressions and convective events. Therefore, the developed dataset has been used as initial land conditions in the weather prediction model and a significant improvement in predicting weather systems such as thunderstorms, monsoon depression and heavy rainfall events could be found, paving way for its use in operational weather forecasting.

Summary

In the recent past, there have been tremendous improvements and development in the field of monsoon climatemodeling, prediction of extreme weather events, prediction of tropical cyclones movement over Indian seas and extended range prediction of monsoon rainfall. Advancement in understanding the monsoon variability in different time-scales are emphasized. Some of the critical developments and findings are listed below.

- Development of the IITM Earth System Model (IITM ESM) for studying long-term climate variability and change.This model is the first climate model from India to contribute to the Coupled Modeling Intercomparison Programme (CMIP) – Phase 6 (CMIP6) and the upcoming Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6).
- Establishing highest resolution (12.5 km) short range ensemble forecasting system globally with 21 ensemble members for ten days forecast. This ensemble prediction system (GEFS at 12.5km) has enabled to initiate much-needed block-level agriculture forecasting system, river basin probabilistic forecast system on an experimental basis.
- Improvement seasonal and extended range forecast systems - CFSv2 model physics and resolution etc.
- Customization of high-resolution mesoscale modeling system and development of coupled HYCOM-HWRF modeling system for TC predictions.
- Highlighted the role interaction among the Atlantic multi-decadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO) in determining the multi-decadal oscillations in Indian summer monsoon rainfall.
- Brought out the importance of the Atlantic Niño, El Niño Modiki, mid-tropospheric cyclones (MTCs), decay phase of El Niño, the Pacific Japan pattern, the Indo-western capacitor mode, Indian Ocean warming, and Wyrtki jets, high latitudes snow covers in modulating Indian Summer Monsoon on an interannual time scale.
- Analysis of the Paleoclimate Modeling Intercomparison Project 3 (*PMIP3*) *models* revealed that the interannual ENSO-Monsoon links have been robust throughout the past millennium, but modulated by the slow changes in the equatorial zonal circulation associated with external changes.
- The impact of easterly waves on northeast monsoon and their association with ENSO is emphasized. Dynamics of Western Disturbances and their influence on winter monsoon rainfall over northwest India and western Himalaya region is highlighted.
- Development of long term (1981-2017) high-resolution soil moisture and soil temperature data over the Indian region.
- Remarkable improvement in the prediction of the track of tropical cyclones over the Bay of Bengal and the Arabian Sea with a high-resolution mesoscale modeling system.
- Development of a dynamical and statistical downscaling technique for improved monthly and seasonal prediction of rainfall and temperature over India.

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