Minireview Article

Destiny of Indian summer monsoon in looming climate change

Abstract

In recent years, with global temperature rise, extreme weather and climate events, especially high temperature heat waves, floods and droughts, occur more frequently. Recent observational and simulation projections with paleoclimate research reported that monsoon rainfall would become uncertain in the forthcoming century. One of the major problems in predicting the ISM is the accumulation of uncertainties arising from the complex role of Anthropocene activities on the climate system. This, in turn, would result in indecisions in the projected Gross Domestic Product (GDP), sustainable growth, and economy. About 21% of the Indian GDP is contributed by Agriculture (arguably the backbone of India's Economy) which itself highly dependent on the spatial and temporal distribution of monsoon rainfall. This paper reviews the projection of the Indian Summer Monsoon (ISM) in looming climate change. Evaluating the uncertainties in future monsoon behavior predictions would facilitate informed decision-making while formulating strategies for a sustainable Economy and energy policy. Reliable predictions of future ISM in the context of climate change are required while formulating adaptation strategies for sustainable growth and water availability.

Keywords: *Climate Change, Global Warming, Indian Summer Monsoon, Future, GDP*

Introduction

The Indian Summer Monsoon may be defined as the sessional reversal of prevailing wind from the Indian Ocean to the Indian landmass in the summer accompanied by precipitation and land to the ocean in the winter devoid of precipitation (Figure 1). The differential specific heating of land and the oceans outcomes with moist air drawn over the continent in the local summer season, when the land is warm relative to the ocean modulated by releasing latent heat associated with rainfall and deep convection produces strong pressure gradients between the land and ocean (Gadgil, 2003). ISM also considered as the manifestation of the meridional overturning circulation across the equator during the summer season (Haug et al., 2003; Gadgil et al., 2003).The summer monsoon is highly variable across Indian subcontinent with northern, north eastern and central regions receiving ☐80% rains than southern part of the country (Figure 2).A large proportion of agricultural production in the region occurs during the Indian summer monsoon season, with most of the region receiving over 80% of its annual rainfall. Monsoon rainfall has always been a critical driver of the Indian Economy (Gadgil & Gadgil, 2006; Turner and Annamalai; 2012). Therefore, understanding the spatiotemporal rainfall pattern and its prediction is essential. Rice is one of the most commonly grown crops of the Kharip season, with India accounting for over 20% of global rice production, the majority of which occurs during and is blessed by the ISM rainfall. Agricultural outcomes are closely connected to the monsoon. For example, in India, a slight change in annual monsoon rainfall causes a significant change in India's annual agricultural gross domestic product (GDP), a significant impact in a country where total agricultural production accounts for almost 21% of GDP. In the recent decade, there has been a substantially increased understanding of the ISM because of the availability of comprehensive and diverse data from ground-based and remote sensing observations, paleoclimate data, and data assimilation and modeling. However, it is challenging to detect ISM's temporal and spatial behavior due to the backdrop of limited historical and long-term natural variability in available instrumental records. Paleoclimate data from marine core and terrestrial archives such as lake sediments, river deposits, peat bogs, tree rings, aeolian deposits, palaeosols, ice core, and speleothems have great potential to capture climatic history beyond the instrumental record and helped to understand the natural variability of the ISM (Gupta et al., 2003; Agnihotri et al., 2002; Sinha et al., 2015). The study of monsoon evolution beyond the instrumental record is thus essential to improve our understanding of monsoon rainfall's natural and anthropogenic forcing mechanisms. ISM interactions and teleconnection on various timescales will enable us to test and enhance climate models in their ability to represent and predict monsoon dynamics and contribute to the climate change discussion (Mohtadi et al., 2016). Nevertheless, this unusual behavior of the ISM makes the life of the one-third population of the world more susceptible in terms of the impact of climate-related natural calamities such as droughts and floods. The ISM region is unique in its geography, topography, demography, and developmental history, including complex forcings from natural and anthropogenic sources.

In the 5th Assessment Report of the IPCC, four representative concentration pathways (RCPs), namely, RCP2.6, RCP4.5, RCP6.0, and RCP8.5, were proposed to depict the future emissions and atmospheric concentrations of greenhouse gases in the 21st century (IPCC, 2014). RCPs were developed considering population, economic growth, water management, energy use, land use patterns, technology, and climate policy. The RCPs were named based on the probable radiative forcing (2.6, 4.5, 6.0, and 8.5 W/m, respectively) in the year 2100 for the pre-industrial levels (Nazarenko et al., 2015). RCP2.6, a mitigation scenario with a deficient forcing level characterized by stringent emission reductions, has a peak followed by a declining trend, with radiative forcing levels peaking at 3 W/m by the mid-century and then declining to 2.6 W/m by the end of the century. RCPs4.5 and 6.0 are medium stabilization scenarios in which the total radiative forcing is stabilized, without overshoot, after the 21st century through various emission reduction strategies. RCP8.5 corresponds to the highest emission level in which the concentrations of greenhouse gases continuously increase over time without any climate change mitigation policies (Van Vuuren et al., 2011).The 6th Assessment Report of the Inter: Governmental Panel on Climate Change, released on August 9, 2021, observed that climate change is widespread, rapid, and intensifying (IPCC, 2021). The 6th IPCC report reported that emissions of greenhouse gases from anthropogenic activities are responsible for approximately 1.1°C of global temperature rising about since last century and finds that averaged over the next 20 years, earth's temperature is expected to cross 1.5°C of warming (IPCC, 2021).

In this article, we attempt to synthesize the results of studies on the observed characteristics of Earth's monsoon systems with recent results advances that provide constraints onprojection of the ISM in climate change, with the aim of taking stock of the progress achieved and identifying possibilities for future work

UNCERTAINTY IN MONSOON PROJECTION

ISM plays a vital role in the hydrological cycle of South Asia, serving as a primary source of the total precipitation in this region. Along with the glacial meltdown, the monsoon is a backbone for the socioeconomic structure of the Indian subcontinent by providing water for the vital agriculture sector and domestic and industrial use. Reliable predictions of future ISM rainfall variability in the context of climate change are required while formulating adaptation strategies. The ISM system is dizzyingly complex, and identifying the processes controlling the various elements of ISM in climate change is hugely challenging. Idealized models and paleoclimatic studies provide a valuable tool for breaking down some of this complexity, and for proposing mechanisms whose relevance can then be investigated in more realistic contexts. However, the prediction of future ISM variability is associated with uncertainties arising at various stages in the observational studies and climate model. The lack of regional coherency in ISM also posed major challenges to the forecasting. Regional correlation note inverse correlation between Eastern Indian Ocean and Bay of Bengal, North India rainfall. Inverse correlation between Central India and Bay of Bengal Rainfall. However positive correlation between North India and Bay of Bengal precipitation (Table 1). The data sets from different region have been studied shows lack of coherence between the trends. A study carried out in central India in the IMD 1^0 data set proposes slight changes to monsoon months rainfall after the 1950 which is contrary to all India monsoon rainfall (Rajeevan et al., 2006; Turner and Annamalai, 2012).

A significant body of work investigating the challenges for the ISM has been taken via modeling and paleoclimatic studies (Mohtadi et al., 2016). The complex interplay between the internal and external forcing factors and serious concern posed by anthropogenic activity leads to considerable uncertainties in climate projections for the monsoon; thus, improvements in delineating the internal and external factors of monsoon variability could reduce uncertainties in near-term climate projections. Very few model studies have been carried out on a pan-India basis to understand monsoon behavior in forthcoming decade around the climate change loop (Goswami, 2006; Roxy et al., 2015; Ali and Mishra, 2018). In particular, model-based studies still need to be included on a regional level. However, paleomonsoon reconstruction using terrestrial and marine proxies' available major part of the Indian Subcontinent. There is a severe need to perform observational and modal simulation studies explicitly focusing on regional-scale monsoon fate in an inevitable climate change scenario. Governments need to look into this matter and grant funds to scientists and research scholars for monsoon simulation.

Climate change can trigger feedback mechanisms within the Earth system that amplify or dampen the impacts on the ISM. For example, changes in land use and vegetation patterns can affect moisture recycling and local climate, potentially influencing the monsoon. However, the specific interactions and feedbacks are complex and still need to be fully understood.Various regional and local factors, including land surface processes, topography, and aerosol concentrations, influence the ISM's behavior. These factors can interact with the larger-scale climate drivers and introduce additional uncertainty into monsoon projection.The ISM is influenced by natural climate variability, such as the El Niño-Southern Oscillation (ENSO). ENSO events in the Pacific Ocean can affect the monsoon patterns in the Indian Ocean region. However, the timing, intensity, and duration of ENSO events are uncertain, making it challenging to determine their specific impacts on the ISM.Future emissions of greenhouse gases, such as carbon dioxide, play a significant role in shaping the climate. However, predicting future emissions is challenging due to various factors, including technological advancements, policy decisions, and socioeconomic changes. Different emissions scenarios lead to varying levels of warming, making it difficult to determine the magnitude of the ISM response precisely

ISM RESPONSE TO CLIMATE CHANGE

Predicting the precise response of the Indian Summer Monsoon (ISM) to future climate change is challenging due to various factors and uncertainties. However, based on current climate models and scientific understanding, here are some potential responses of the ISM in the forthcoming climate change. Climate change is an inevitable phenomenon and its effects are felt both in the Indian Subcontinent and all over the globe (IPCC, 2021; Barnosky et al., 2011). In the recent time of the geological history Earth's temperature rise by an average of 0.08^0 per decade since late 19^{th} century and the rate of warming since 1981 is more than twice 0.18^0 decade (Foster, 2022).The Indian summer monsoon rainfall (ISMR) has been declining since the 1950s. However, since 2002 it is reported to have revived. For these observed changes in the monsoon rainfall, several explanations have been reported i.e. short period trend may part of multidecadal to centennial variability which is driven by the forcing from solar cycle (Agnihotri et al., 2002); Atlantic multidecadal Oscillation (AMO) (Wang et al., 2013), Pacific decadal oscillation (PDO) (Raghavan and Sugi, 2003) . The ISM rainfall varies at multiple temporal scales, from sub-seasonal to decadal to multi-centennial scale and local to regional scale, and affects the socioeconomic structure of the one-third population of the world (IPCC, 2021). A reliable forecast of ISM is indispensable to mitigating the often catastrophic consequences of monsoon rainfall anomalies, such as floods and droughts, famine, and economic losses. However, in the backdrop of climate change, ISM rainfall remains difficult to predict (Flato et al., 2013; Mohdati et al., 2016). Several attempts have been made in recent years to project monsoon circulation under the different scenarios of human-induced radiative forcing with the general circulation models (GCMs) (Douville et al., 2000; Ueda et al., 2006). Recently; the monsoon response to global warming is examined using a state-of-the-art atmosphere and eight ocean-coupled GCMs. It is reported that the increase in GHG forcing caused enhanced monsoon rainfall by about 13% in the 22nd century, while the large-scale monsoon circulation became weak (Ueda et al., 2006).Coupled Model Intercomparison Model 5 (CMIP5)and CMIP6 strongly suggest that monsoon fed area, annual range, mean precipitation are likely to increase by the end of the 21 century (Kitoh et al. 2013; Lee et al. 2019). The increase in the monsoon in the NH will be manifested by the earlier or unchanged onset dates and delayed retreat from land areas (Lee and Wang, 2014).Climate models generally project an increase in overall rainfall during the monsoon season. Warmer temperatures can enhance the moisture content in the atmosphere, leading to heavier rain in some regions. This could have implications for flooding and water resource management.While the overall rainfall is expected to increase, precipitation may be redistributed across different regions. Some areas could experience more intense rainfall, while others may receive less. These shifts could impact agriculture, water availability, and regional ecosystemsChanges in monsoon onset and withdrawal: Future climate change might affect the monsoon onset and withdrawal timing. While the exact differences are uncertain, studies suggest that the monsoon onset could become more erratic or delayed, with implications for agricultural planning and water management.While the consensus among climate models and scientific studies points towards an increase in Indian Summer Monsoon (ISM) rainfall in response to climate change, it is essential to acknowledge that there can be variations and uncertainties in regional projections. While the majority of studies indicate an intensification of the ISM, however some can provide information on a study that suggests a decrease in the monsoon rainfall:One notable study published in the journal Nature by Chakraborty et al. 2019suggested a potential decrease in ISM rainfall in the future. The study used a climate model ensemble to project the ISM response to increased greenhouse gas concentrations. The findings indicated that the ISM rainfall could decrease by up to 40% under a high-emission scenario by the end of the 21st century. The study attributed this projected decline to changes in large-scale atmospheric circulation patterns, particularly the weakening of the meridional temperature gradient.

It is important to note that this study represents one perspective and that it is necessary to consider a broader range of research to fully understand the complex behavior of the ISM in a changing climate. Climate models have limitations, and different models may produce varied results. Other studies may provide different projections or emphasize various aspects of the ISM response to climate change. There are findings which suggest that anthropogenic aerosols have influenced decreased the Northern Hemisphere land monsoon in the South Asia during the late 20th century. A recent study based on a climate model demonstrated that global warming could strengthen the ENSO-monsoon relationship (Xu et al., 2023). The increase of emission of scattering and absorbing enhance the radiative forcing limits the Sun radiation reaching the Earth Surface

Overall, while most studies suggest an increase in ISM rainfall, it is essential to consider multiple research sources and the inherent uncertainties involved in climate modeling to understand the potential changes in the Indian Summer Monsoon in the future.

Conclusion

Climate models based on an extended analysis of the ISM suggest that increasing greenhouse gas concentrations may led an increase in precipitation during upcoming future. According to the simulations, climate warming will continue both in Indian subcontinent and in the world, leading to more frequent occurrence of dry thunderstorms, increased number of Extreme rain days with flood alert, higher flood risks, and greater challenges in monsoon forecasting. Therefore, we must strengthen studies on the impacts of climate change on monsoon, improve the monitoring, prediction and alert system for extreme rain events, and raise public awareness and knowledge of water management.Climate change is likely to contribute to increased variability in monsoon rainfall and an increase in extreme weather events such as heavy rainfall, cyclones, and storms. This variability can pose challenges for agriculture, infrastructure, and disaster management.

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Table 1. Rainfall index

	EIO (Eastern Indian Ocean)	**BOB (Bay of Bengal)**	**CI (Central India)**	**WG (Western Ghat)**	**AIRI (All India Rainfall Index)**
EIO	1				
BOB	-0.24	1			
CI	0.1	-0.37	1		
NI	-0.21	0.32	0.35	1	
WG	0.18	-0.06	0.59	0.13	1
AIRI	-0.16	0.06	0.6	0.56	0.48

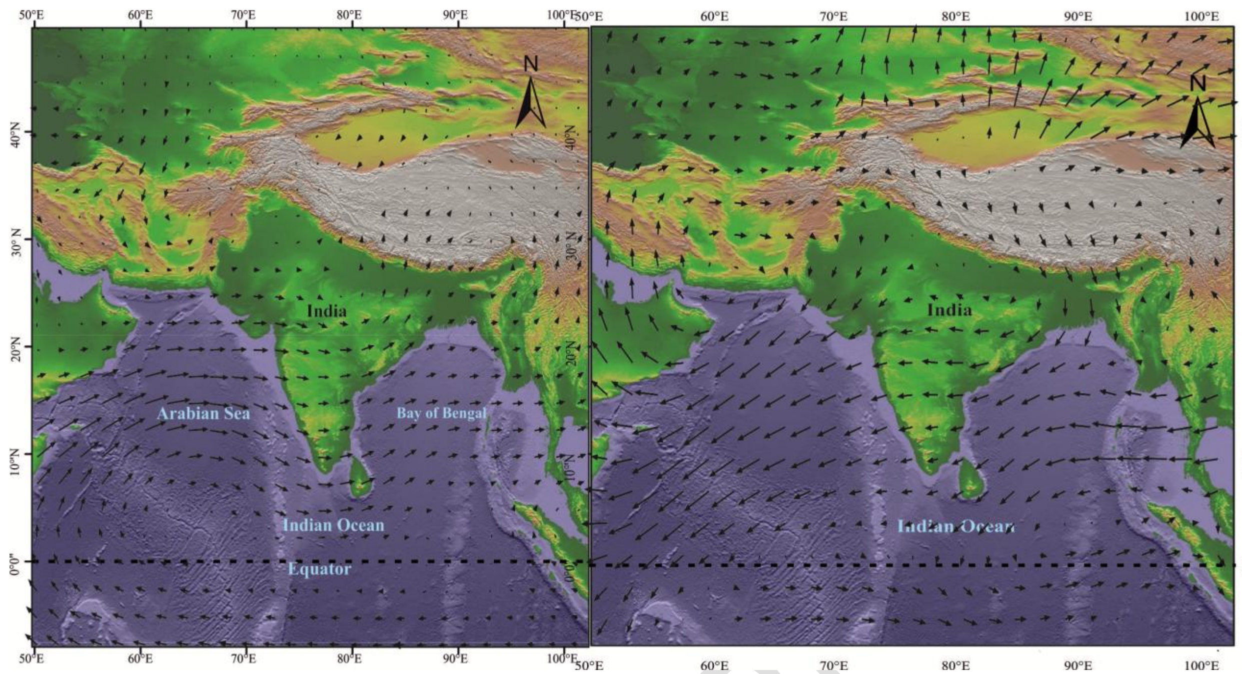

Fig 1. Map showing rainfall index