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Climate Dynamics: Unravelling the Characteristics of Monsoon Semipermanent Features

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Abstract

The Indian summer monsoon (ISM) spans a crucial four-month period, unfolding from June to September (JJAS), inundating the Indian subcontinent with extensive rainfall. The stark contrast in land-sea heating stands as a key catalyst for the ISM phenomenon. Managing the ISM hinges on the orchestration of various monsoon semi-permanent features (MSF), encompassing entities like the Pakistan heat low, cross-equatorial low-level jet over the Arabian Sea, the tropical easterly jet over the Indian Ocean at 200 hPa, Mascarene High, and the seasonal anti-cyclone over Tibet. Fluctuations in these MSF wield significant influence over the Indian Summer Monsoon Rainfall (ISMR), making it crucial to scrutinize their structure and variability amidst evolving climate scenarios, foreseeing their impact on future monsoons. Additionally, the ISM displays internal variability, oscillating between deficit and surplus years. Understanding how MSF impacts this variability becomes pivotal. Therefore, the main focus of the study is to investigate the fluctuations in rainfall during JJAS across the Indian monsoon core region, as well as the unique features of the Monsoon Surge Frequency (MSF) in two divergent monsoon years. Prior research has underscored the pivotal role of the monsoon core zone in shaping ISM, hence focusing on this zone for the rainfall study. To achieve these objectives, datasets from reputable sources like the 5th generation European Centre for Medium-Range Weather Forecasts (ERA5), India Meteorological Department (IMD) rainfall records from 1981-2020, and Coupled Model Intercomparison Project Phase 6 (CMIP6) spanning 2015-2021 under four distinct SSP scenarios are employed. These datasets aid in deciphering alterations in MSF and their repercussions on ISM-induced rainfall. The assessment of rainfall percentage departure utilizes methodologies in line with Rajeevan et al.'s (2010) framework, ensuring comprehensive and comparable analyses across datasets. This comprehensive study amalgamates various datasets and analytical approaches to illuminate the complex interplay between MSF, rainfall variations, and the dynamics of the Indian summer monsoon, laying the groundwork for informed assessments of future climate scenarios and their potential implications on this critical meteorological phenomenon.

Keywords: Monsoon, India, Rainfall, Climate, ISMR, SMF.

1. Introduction

1.1: Semipermanent Features

Monsoons represent a prevalent phenomenon in tropical and subtropical regions worldwide, typified by distinct seasonal patterns: wet summers and comparatively drier winters, accompanied by a reversal in prevailing winds. The Indian Summer Monsoon (ISM) owes its existence to the assessment of land-sea heating dynamics within the Indian Ocean and the vast Asian landmass. This variability inherent in the ISM exerts significant influence on India's socioeconomic landscape, given that 70-80% of the annual rainfall across the Indian subcontinent is contributed by the ISM. Its defining characteristics include a lower-level (850 hPa) south-westerly jet and an upper-level (200 hPa) easterly jet, culminating in extensive rainfall over a substantial expanse of the Indian subcontinent during the four-month span from June to September. The ISM's dynamics are intricately managed by semi-permanent features such as the heat low over the northwest region of India, the Tibetan High, Mascarene High, the tropical easterly jet, and the south-westerly jet. Renowned for its vigor and influence, the ISM stands as one of the most dynamic and influential monsoon systems globally (Pant and Rupa Kumar, 1997). These monsoonal variations play a pivotal role in shaping the climatic patterns and economic activities of the region, impacting agriculture, water resources, and various sectors reliant on the monsoon-induced rainfall. Understanding the intricacies of the ISM's behaviour and the factors governing its fluctuations is vital for formulating effective strategies to manage and adapt to its diverse impacts on the Indian subcontinent. Moisture carried across from the Arabian Sea contributes significantly to the precipitation occurring over the Indian Ocean, spanning towards peninsular India and the Bay of Bengal. The yearly progression of the Indian Summer Monsoon (ISM) demonstrates variability across different time scales, ranging from intra-seasonal changes to decadal shifts, as highlighted in the study by Webster et al. in 1998. A prominent feature within the ISM, the Low-Level Jet (LLJ), plays a dominant role in shaping the Indian Summer Monsoon Rainfall (ISMR), as emphasized by Joseph and Sijikumar in 2004.

The Somali Jet serves as the upper-level northern component of the low-level cross-equatorial airflow within the Indian Ocean, playing a crucial role in the Indian monsoon system. During boreal summer, this airflow courses over the Arabian Sea along the coast of Somalia, acting as the primary source of moisture for the monsoon. By July, the easterly airflow becomes more concentrated south of the subtropical ridge across Asia, forming a jet stream near the latitude of Chennai at 150 hPa. This jet stream spans from the eastern coast of Vietnam to the western coast of Africa, typically positioning itself around 10° N over the African continent. To deepen our understanding, a comparative analysis was undertaken, examining the upper-level large-scale circulation characteristics. This analysis utilized a composite of five years representing surplus Indian Summer Monsoon Rainfall (ISMR) against years classified as normal or deficit in ISMR. By scrutinizing these circulation patterns, we aim to shed light on the variability and distinct features associated with different ISMR conditions, thus advancing our knowledge in the field of monsoons. Rao et al. (2004) noted a declining trend in the strength of the Tropical Easterly Jet (TEJ) throughout the Asian Summer Monsoon season in recent years. Another significant feature is the Pak–India low, a prominent low-pressure area over Pakistan and northern India, often referred to as the "heat" low due to its dependence on surface thermal phenomena for its formation. Our investigation delves into observational data and diagnostic analyses to understand the influence of models on the Pak–India low. We acknowledge the multifaceted influences on this phenomenon, including both regional and distant factors. Regionally, the Hindu Kush mountains exert a significant impact, surpassing the effects of land-surface warming and its associated consequences. By comprehensively examining these factors, we aim to unravel the complex interactions shaping the Pak–India low and its implications for the broader monsoon system. Through this research, we strive to contribute valuable insights into the mechanisms driving monsoon variability and its broader climatic implications. At the heart of the South Asian summer monsoon lies the monsoon trough (MT), a significant semi-permanent feature. Stretching from northwestern India and Pakistan to the Gangetic plains and the Bay of Bengal, the MT represents a crucial low-pressure zone within the monsoon dynamics. Extensive research by scholars like Anjaneyalu (1969), Rao (1976), Koteswaram and Rao (1963), Krishnamurti and Surgi (1987), Sikka and Narasimha (1995), and Wang (2004) has thoroughly documented the characteristics of the MT and its impacts on the South Asian monsoon system. Their studies have greatly contributed to our understanding of this essential component of the region's climate system. The east-west oriented monsoon trough (MT) plays a crucial role in governing the active and break phases of the monsoon, consequently influencing the seasonal and interannual rainfall variations across the Indian subcontinent. Often dubbed the "third pole of the Earth" and "summit of the planet," the Tibetan Plateau (TP) boasts intricate geological features of global significance. Operating as an elevated heat source within the middle troposphere, the TP induces a significant temperature contrast with the surrounding lower atmosphere. During the monsoon season, the Tibetan High materializes as a warm anticyclone, triggering clockwise wind patterns in the Northern Hemisphere. This region, situated at approximately 28˚N latitude and 98˚E longitude, experiences consistent outflow of winds in the middle to upper troposphere. An equally significant semi-permanent feature, the Mascarene high, serves as a cornerstone of the Asian Summer monsoon. Positioned within the South-Indian Ocean between latitudes 25˚S-35˚S and longitudes 40˚E-90˚E, this high-pressure zone near the Mascarene Island contributes substantially to the monsoonal dynamics. It intensifies the planetary boundary layer's heating, significantly influencing atmospheric circulation patterns. In their study, Knutson and Manabe (1995) noted a trend in international warming simulations indicating a consistent weakening of Monsoonal flows and the broader tropical large-scale flow.

A hotter climate tends to produce stronger moisture convergence despite this weakening, as noted by a number of researchers, including Douville et al. (2000), Giorgi et al. (2001a, 2001b), Stephenson et al. (2001), Dairaku and Emori (2006), and Ueda et al. (2006). Elevated monsoonal precipitation levels are frequently the consequence of accelerated moisture convergence predominating over a weakening of the monsoon circulation. According to Stephenson et al. (2001), there are a number of physiological and dynamical components of the monsoon circulation where the effects of climate change could show themselves in different ways. In a second study, Degtyarev (2008) used a numerical model to examine how the monsoon circulation changed in response to various carbon dioxide concentrations. Monsoon circulation indices obtained from simulated zonal wind speeds in both the upper and lower troposphere, as well as model-generated precipitation rates, were analysed in both investigations.

Though the main monsoon circulation appears to be diminishing, Douville et al. (2000) observed notable variations in midsummer monsoon precipitation. These variations carry significant socio-economic implications for regions inhabited by over 70% of the global population. Comprehending the monsoon is essential for comprehending global atmospheric circulation and climate change, as well as for preventing, mitigating, and promoting long-term development after disasters. Important surface phenomena linked with the South Asian monsoon continue to be the Mascarene High in the southwest Indian Ocean, the Heat Low in the arid parts of the Middle East, the Monsoon Trough covering India, and the Cross-equatorial Monsoon Low-Level Jet. Furthermore, in the higher troposphere, the Tibetan Anticyclone is positioned between the Tropical Easterly Jet-stream (TEJ) and the Northern Subtropical Westerly Jet-stream (NSWJ). These components collaboratively contribute to the formation of the monsoon's vertical (Hadley) circulation. Understanding the interplay of these elements is essential for deciphering the complexities of the monsoon system and its impacts on regional and global climates. Understanding and studying these components are pivotal for comprehending the intricate dynamics of the monsoon and its profound impact on regional and global climate patterns. The research article explores the environmental consequences of monsoon semi-permanent traits in the face of climate change. Focusing on the intricate dynamics of monsoon systems, it investigates their evolving patterns, impact on ecosystems, and potential repercussions due to climate variability. By analysing the interplay between monsoons and the environment, the study aims to elucidate shifts in rainfall, temperature, and ecological stability. Through comprehensive assessments, it intends to offer insights into how altered monsoon traits could affect biodiversity, agriculture, and water resources. Ultimately, this research endeavours to provide a nuanced understanding of the environmental implications of changing monsoon patterns in the context of climate change.

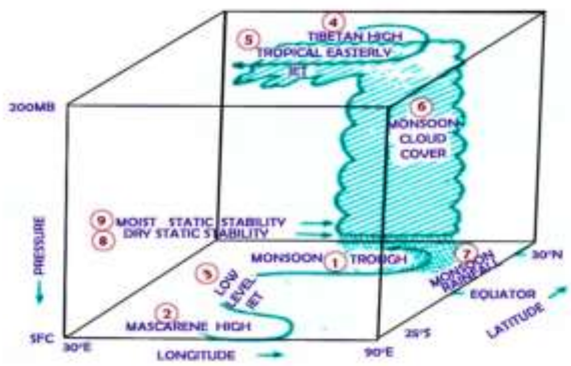

Figure 1. Schematic view of the semi-permanent features during the Asian summer monsoon system (Krishnamurti and Bhalme, 1976).

Convection along the Monsoon Trough propels air upward, contributing to the formation of the Tibetan High. As this air mass progresses southward, it generates the Tropical Easterly Jetstream, descending near latitude 30S at the Mascarene High. The return flow materializes as the Low-Level Jetstream. This sequence involves robust convection in the Monsoon Trough, followed by the emergence of a strong Tibetan High and the Tropical Easterly Jetstream. This is accompanied by heightened pressure at the Mascarene High and a vigorous Low-Level Jetstream, leading to increased rainfall over India. However, the Monsoon Trough zone experiences a decline in conditional instability, weakening the vertical circulation, as depicted in Figure 1. Table 1 provides a comprehensive overview of various monsoon semi-permanent features, detailing their corresponding meteorological parameters such as mean sea level pressure, surface air temperature, and wind patterns. These features include the Tibetan High, Tropical Easterly Jetstream, Mascarene High, and Low-Level Jetstream. The table delineates their formation locations and the duration required for their strengthening, offering crucial insights into the dynamics and characteristics of these features within the monsoon system.

Table:1 It denotes the semi-permanent features along with their corresponding meteorological parameters, geographical location, and duration.

Semipermanent features	Pressure (High/low)	Temper-ature (High/Low)	Meteorological Parameter	Pressure level(hPa)	Location	Duration
Monsoon Trough	Low		Outgoing Longwave Radiation (OLR)	Surface	Over Indian region(16-28N,65-100E)	July, August
Mascarene High	High		Wind Speed and Direction, Mean Sea level Pressure	850	In the Indian Ocean near the Mascarene Islands (20°S–40°S and 45°E–100°E)	May, June, July
Somali Jet			Wind speed and Direction	850	Arabian Sea (35E-100E and 30N -10S)	July, August
Tibetan High	High		Wind Speed and Direction, Mean Sea level Pressure	200	Tibetan Plateau (60E-105E and 40N-20N)	July
Pakistan Heat Low	Low	High	Air temperature (2m), Mean Sea level Pressure	Surface	NW Rajasthan and adjoining Pakistan (50E-85E and 15N-35N)	April, May, June
Tropical Easterly Jet			Wind speed and Direction	200	Southern Asia (40N-10S and 30E-100E)	July, August

2. Literature Survey

Throughout the June to September Indian summer monsoon period, a constellation of semi-permanent features (SMFs) emerges over the Indian subcontinent, profoundly influencing the intensity of Indian summer monsoon rainfall (ISMR). The Heat Low (HL), Monsoon Trough (MT), Tibetan Anticyclone (TA), Tropical Easterly Jet (TEJ), and Low-Level Jet (LLJ), commonly referred to as the Somali jet, are some of these SMFs. The presence of these SMFs, particularly the HL, MT, TA, TEJ, and LLJ, is instrumental in shaping the dynamics of the Indian summer monsoon. Notably, the geographical barriers presented by the Himalayas and the Tibetan regions can induce westerly flows, potentially weakening the easterly jet, especially in a warmer climate scenario. This alteration in jet stream dynamics can significantly influence the spatial distribution and magnitude of mean ISMR. The behaviour of the monsoon system is largely controlled by the interaction of multiple atmospheric phenomena, such as the anomalous westerly flow over the Indian Ocean at 200 hPa and the anticyclonic flow in the Arabian Sea at 850 hPa. These atmospheric patterns contribute to the spatial variability and overall strength of ISMR during the summer monsoon season. During surplus years, characterized by above-average ISMR, the Somali jet exhibits robustness, indicating enhanced monsoon circulation. This robust circulation pattern, driven by the LLJ, facilitates the transport of moisture-laden air masses from the Indian Ocean towards the Indian subcontinent, augmenting rainfall activity. Understanding the intricate relationships between these SMFs and their impact on ISMR is essential for predicting and managing the Indian summer monsoon. By elucidating the mechanisms underlying monsoon variability, researchers can improve seasonal forecasting models and develop strategies to mitigate the socio-economic impacts of monsoon-related phenomena such as floods and droughts.

Climate Dynamics: Unraveling the Characteristics of Monsoon Semipermanent Features conducts an extensive literature survey to illuminate the intricate characteristics of monsoon semi-permanent features, with a particular focus on the monsoon trough. The survey encompasses a breadth of scholarly works spanning several decades, aiming to consolidate existing knowledge and identify gaps in understanding. Notably, studies by different researcher and contributed significantly to this field, offering valuable insights into the spatial and temporal dynamics of monsoon features and their impacts on the broader climate system. Meany's pioneering work laid the foundation for understanding the structure and behavior of the monsoon trough, highlighting its role as a crucial determinant of monsoon rainfall distribution across South Asia. Collectively, these studies have significantly advanced our understanding of monsoon semi-permanent features, elucidating their characteristics, dynamics, and broader implications for regional climate variability and change. However, despite substantial progress, several key research gaps remain, particularly regarding the interactions between monsoon features and local land surface processes, as well as the role of anthropogenic forcing in modulating monsoon behavior. Addressing these knowledge gaps will be crucial for improving the accuracy and reliability of monsoon predictions and enhancing our ability to adapt to future climate challenges in the South Asian region and beyond.

The Tropical Easterly Jet tends to be weaker across northern India but gains strength in a southwest-to-west direction at lower latitudes, contributing to an enhanced monsoon circulation. Moreover, in wetter years, the Somali jet's center shifts eastward, further amplifying the circulation patterns and consequently leading to increased ISMR. These interplays among the various semi-permanent features during the Indian summer monsoon season not only influence the intensity and direction of prevailing winds but also contribute significantly to the overall dynamics and magnitude of rainfall patterns across the region. The ensemble results from multiple models spanning the period 2005–2099 portray distinctive trends in the Somali Jet's behavior across different phases of the twenty-first century. During the early phase (2010–2040), there's evidence of a weakened Somali Jet, followed by its peak strength observed in the mid-twenty-first century (2050–2060), and ultimately culminating in the weakest Somali Jet by the century's end (2070–2090). Comparatively, the overall intensity of the Somali Jet shows a consistent weakening trend when contrasted with the period from 1976–1999, reaching its lowest levels towards the conclusion of the twenty-first century. The cross-equatorial Low-Level Jet (LLJ) displays varying trajectories, starting as a southerly current near the East African coast and transitioning into a westerly current as it crosses India, spanning latitudes from the equator up to 25 N. The LLJ's central axis traverses peninsular India around latitude 15N, particularly during periods of subdued monsoon activity. Between the equator and 10 N, the LLJ from the central Arabian Sea diverts southeastward, skirting eastward near Sri Lanka during phases of a weakened monsoon. During this time, a less pronounced LLJ axis might be discernible across northern India, approximately around latitude 25N. These varying LLJ dynamics signify the complex nature of monsoonal circulation patterns during different phases of the twenty-first century.

3. Data and Methodology

3.1 Data

Various datasets from multiple sources were utilized for this study. The primary dataset comprises atmospheric and surface variables sourced from the ERA-5 atmospheric reanalysis (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), IMD observational data (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html), and CMIP6 model output datasets (https://cds.climate.copernicus.eu), covering the time span of 1981 to 2020 and 2015-2024 respectively. It includes characteristics of mean Indian Summer Monsoon Rainfall (ISMR) in June to September (JJAS), monthly mean wind at 850 hPa and 200 hPa, surface temperature, and sea level pressure from 1981–2020. The horizontal resolution for ERA-5 reanalysis (0.25°×0.25°) and IMD (0.25°×0.25°) is employed as shown in Table 2. Monthly averages of Outgoing Longwave Radiation (OLR) dataset with a spatial grid resolution of 2.5º*2.5º and diurnal temporal resolution were acquired from the National Oceanic and Atmospheric Administration (NOAA) (https://psl.noaa.gov/data/reanalysis). Additionally, the monthly OLR data analyzed in this study spans from 1981 to 2020 with a spatial resolution of 2.5˚*2.5˚. The Scenario Model Intercomparison Project (Scenario-MIP) is a central initiative within Phase 6 of the Coupled Model Intercomparison Project (CMIP6). Its primary goal is to furnish a range of climate projections derived from multiple models. These projections are based on various scenarios reflecting potential future emissions and alterations in land use, formulated through integrated assessment models. The Scenario-MIP experiment encompasses a set of pathways outlining future emissions and concentration levels. These scenarios delineate potential developments in human-induced factors contributing to climate change. Notably, the Indian Summer Monsoon (ISM) is predominantly influenced by semi-permanent features within the climate system.

Table:2 Description of the different datasets used for this study

S. No	Data	Variables	Frequency	Duration	Spatial Resolution
1	ERA5 (ECMWF) Reanalysis data	Outgoing longwave radiation(W/m2) Air temperature(2m) (˚C) Mean Sea level Pressure(hPa) Zonal and Meridional wind(m/s) Rainfall(mm)	Monthly	1981-2020	0.25° x 0.25°
2	NCEP/NCAR Reanalysis	OLR (W/m2)	Monthly	1981-2020	0.25° x 0.25°
3	IMD Pune	Rainfall(mm)	Daily	1981-2020	0.25° x 0.25°
4	CMIP6	Outgoing longwave radiation(W/m2) Air temperature(2m)(˚C) Mean Sea level Pressure(hPa) Zonal and Meridional wind(m/s) Rainfall(mm)	Monthly	2015-2024	2.5˚×2.5˚

3.2 Methodology

The study focuses on the monsoon core zone delineated in Figure 1. This region, previously identified as crucial to the Indian summer monsoon, spans approximately from 18° N to 28° N latitude and 65° E to 88° E longitude, based on research by Rajeevan et al. (2010). This zone is of particular interest due to its significant influence on the Indian monsoon system. Within the selected monsoon core region, rainfall data from the Indian Meteorological Department (IMD) and the ERA5 dataset are utilized to identify years categorized as experiencing either rainfall shortage or surplus. These years are crucial for comparative analysis to understand variations in monsoon behavior. The departure of rainfall from normal conditions is calculated as a percentage for both IMD and ERA5 datasets. This calculation involves comparing the observed rainfall in a specific year to the long-term average or climatological norm for that region. The percentage departure provides a quantitative measure of how much the observed rainfall deviates from the expected or typical values.

The methodology described enables the researchers to focus their analysis on a specific region known to be pivotal in the Indian summer monsoon. By utilizing data from both IMD and ERA5 datasets, the study ensures comprehensive coverage and robustness in identifying rainfall anomalies. The calculation of rainfall percentage departure facilitates the quantification of deviations in rainfall patterns, enabling comparisons between surplus and shortage years within the monsoon core region. Overall, this methodology provides a structured approach for investigating rainfall variations and their implications for the Indian monsoon system. The monsoon core zone, delineated in Fig. 1, will serve as the focal area for the rainfall study due to its recognized significance to the Indian summer monsoon, spanning approximately from 18° N to 28° N and 65° E to 88° E, as highlighted in a previous study (Rajeevan et al., 2010). Within this core region, both the Indian Meteorological Department (IMD) and ERA datasets are employed to identify years characterized by rainfall shortages and surpluses, facilitating a comprehensive analysis of monsoon variability and its implications.

IMD and ERA5 dataset's rainfall percentage departure is calculated as follows: R = (actual mean – climatology mean)/climatology mean)*100

Table:1 Criteria for identification of Surplus, Deficit, and Normal Years

Rainfall Percentage Departure (R in %)	Identification of Years
R>10	Surplus
-10<R>10	Normal
R<10	Deficit

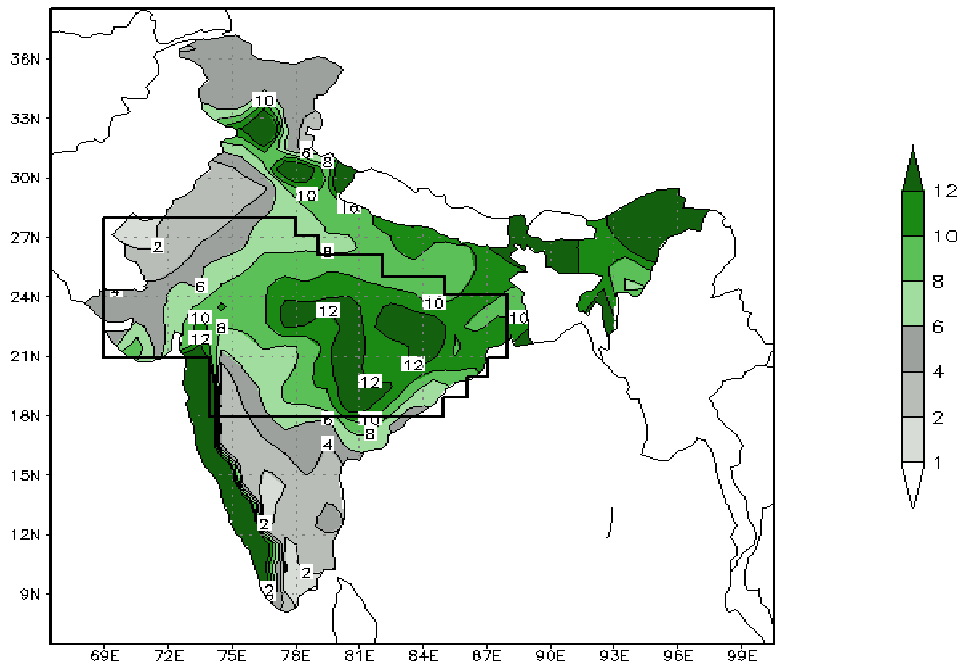

Figure: 2 For the years 1981–2020, the monsoon core zone (black color box) is used to determine the surplus, deficit, and normal year. The rainfall (mm/day) during the boreal summer monsoon is also displayed.

4. Result and Discussion

4.1 Surplus and Deficit

The scope of examining the surplus and deficit of the Indian Summer Monsoon rainfall encompasses a multifaceted analysis of its impacts and implications. It involves investigating the geographical distribution of surplus and deficit regions, understanding the meteorological factors influencing these variations, and assessing their consequences on agriculture, water resources, economy, and society. By scrutinizing historical data, climate models, and regional trends, the scope extends to predicting potential patterns of surplus and deficit, enabling proactive measures for water management, agricultural planning, disaster preparedness, and policy formulation. Additionally, the scope involves exploring adaptive strategies, socio-economic vulnerabilities, and the overall resilience of regions experiencing either surplus or deficit in monsoon rainfall. The Indian monsoon, a vital component of the region's climate system, exhibits considerable variability, resulting in surplus or deficit rainfall conditions that significantly impact agriculture, water resources, and socio-economic activities. This research article provides an in-depth analysis of surplus and deficit Indian monsoon systems, exploring their underlying mechanisms, spatiotemporal characteristics, impacts, and future projections. Through a comprehensive review of existing literature and empirical data, key factors influencing the occurrence and persistence of surplus and deficit monsoon years are identified, including large-scale atmospheric circulation patterns, sea surface temperature anomalies, land-ocean temperature gradients, and topographical features. Moreover, the socio-economic implications of these extreme monsoon events are examined, highlighting their effects on crop yields, food security, water availability, and rural livelihoods. Furthermore, the article discusses recent advances in monsoon prediction models and forecasting techniques, aiming to improve our ability to anticipate and mitigate the impacts of surplus and deficit monsoon years. Finally, future research directions are outlined, emphasizing the need for interdisciplinary approaches to enhance our understanding of the complex interactions driving Indian monsoon variability and to develop effective adaptation strategies in a changing climate. The Indian monsoon, characterized by its seasonal reversal of winds and associated rainfall, plays a pivotal role in sustaining agricultural productivity, water resources, and ecosystems across the Indian subcontinent. However, the monsoon's inherent variability often leads to deviations from normal rainfall patterns, resulting in surplus or deficit monsoon years with significant socio-economic repercussions. While surplus monsoon years can foster agricultural productivity and replenish water reservoirs, deficit monsoon years pose challenges such as droughts, water scarcity, and crop failures, affecting millions of people dependent on rainfed agriculture. Understanding the dynamics of surplus and deficit Indian monsoon systems is therefore essential for effective climate risk management and adaptation planning.

Surplus and deficit monsoon years are influenced by a multitude of factors, including large-scale atmospheric circulation patterns, sea surface temperature anomalies, land-ocean temperature gradients, and topographical features. The El Niño-Southern Oscillation (ENSO) phenomenon, characterized by anomalous warming or cooling of sea surface temperatures in the tropical Pacific Ocean, exerts a significant influence on Indian monsoon variability. El Niño events are often associated with reduced rainfall over the Indian subcontinent, leading to deficit monsoon conditions, while La Niña events tend to enhance monsoon rainfall, resulting in surplus years. Additionally, other climate modes such as the Indian Ocean Dipole (IOD) and the Madden-Julian Oscillation (MJO) can modulate monsoon variability, further complicating the prediction of surplus and deficit monsoon years. The impacts of surplus and deficit monsoon years are wide-ranging and profound, affecting various sectors of the economy and society. In surplus monsoon years, abundant rainfall can boost agricultural production, increase water availability for irrigation, and support hydropower generation. However, excessive rainfall may also lead to flooding, landslides, and waterlogging, causing damage to crops, infrastructure, and livelihoods. Conversely, deficit monsoon years can result in droughts, water stress, and crop failures, jeopardizing food security, rural livelihoods, and socio-economic stability. Moreover, the uneven spatial distribution of rainfall during surplus and deficit monsoon years can exacerbate regional disparities in water availability and agricultural productivity, further exacerbating socio-economic inequalities. Efforts to improve the prediction and forecasting of surplus and deficit monsoon years have intensified in recent years, driven by advancements in climate modelling, data assimilation techniques, and remote sensing technologies. State-of-the-art climate models, such as coupled atmosphere-ocean models and dynamical seasonal prediction systems, offer valuable insights into the potential drivers and predictors of monsoon variability at various temporal and spatial scales. Additionally, statistical models and machine learning algorithms have been employed to develop probabilistic forecasts of surplus and deficit monsoon years, incorporating a wide range of atmospheric, oceanic, and land surface variables as predictors. Furthermore, the integration of satellite observations, ground-based measurements, and citizen science initiatives has enhanced our ability to monitor and predict monsoon variability in real-time, enabling early warning systems and adaptive strategies to mitigate the impacts of extreme monsoon events.

Despite significant progress in understanding surplus and deficit Indian monsoon systems, several research gaps persist, necessitating further investigation to enhance predictive capabilities and inform adaptation strategies in a changing climate. Future research efforts should focus on improving the representation of regional climate processes, feedback mechanisms, and teleconnections in numerical models, thereby reducing uncertainties in monsoon prediction and projection. Moreover, interdisciplinary research collaborations are essential to integrate socio-economic, ecological, and governance perspectives into monsoon risk assessment and management strategies, fostering resilience and sustainability in vulnerable regions. Additionally, the development of innovative early warning systems, risk assessment tools, and decision support frameworks can empower stakeholders to make informed decisions and enhance adaptive capacity in response to surplus and deficit monsoon years.

Surplus and deficit Indian monsoon systems represent critical challenges and opportunities for sustainable development and climate resilience in the region. By elucidating the underlying mechanisms, impacts, and future projections of surplus and deficit monsoon years, this research article seeks to inform policy-makers, practitioners, and researchers about the complexities of Indian monsoon variability and the urgent need for proactive adaptation measures. By adopting an integrated approach that combines scientific knowledge, indigenous wisdom, and community-based solutions, we can enhance our resilience to extreme monsoon events and build a more resilient and equitable society in the face of climate change. Between June and September, the Indian summer monsoon rainfall (ISMR) typically accounts for approximately 80% of the annual precipitation. The reliability, unpredictability, and instances of extreme summer monsoon rains significantly influence India's agricultural yields, economy, and overall societal welfare. Due to its intricate nature and profound implications for the populace, the examination of variability in the Indian summer monsoon stands as a significant and socially pertinent scientific pursuit (Webster et al., 1998). To investigate rainfall patterns, an analysis was conducted using both raw data and anomalies derived from IMD and ERA5 rainfall datasets. The composite of five years each for deficit (1982, 1985, 1986, 1987, 2002) and surplus (2007, 2011, 2013, 2019, 2020) conditions was compiled for the monsoon core zone. Subsequently, for further examination, a common composite of five deficit and surplus years was extracted from both IMD and ERA5 datasets. Anomaly analysis (depicted in Fig-4) was computed by subtracting the mean climatological value from the respective yearly mean, divided by the climatological mean. Table-3 provides a representation of the five common surplus and deficit years retrieved from both IMD and ERA5 datasets. A comparative assessment of IMD (4-a) showcased an overestimation of rainfall in Madhya Pradesh, the monsoon core zone, and the Southeastern region, along with underestimated rainfall in the North-eastern part of India. Conversely, the ERA5 analysis (4-b) revealed a positive anomaly in the central part of the monsoon core zone (with the highest positive anomaly), the Southeastern region, as well as the Western Ghats and Gujarat during surplus-deficit years. This disparity highlights contrasting rainfall distributions between the observed JJAS (June to September) rainfall in IMD and ERA5 datasets during surplus and deficit monsoon years. The occurrence of surplus and deficient monsoon seasons significantly impacts various sectors, particularly agriculture, economy, and water resources management. Surplus monsoon seasons, characterized by above-average rainfall, can lead to agricultural productivity booms, increased water reservoir levels, and economic growth. However, excessive rainfall may also result in flooding and soil erosion, posing challenges for infrastructure and agricultural sustainability. Conversely, deficient monsoon seasons, marked by below-average rainfall, can cause drought, crop failures, and water scarcity, exacerbating food insecurity and economic distress. Understanding the dynamics of surplus and deficient monsoon patterns is crucial for effective adaptation and mitigation strategies in vulnerable regions.

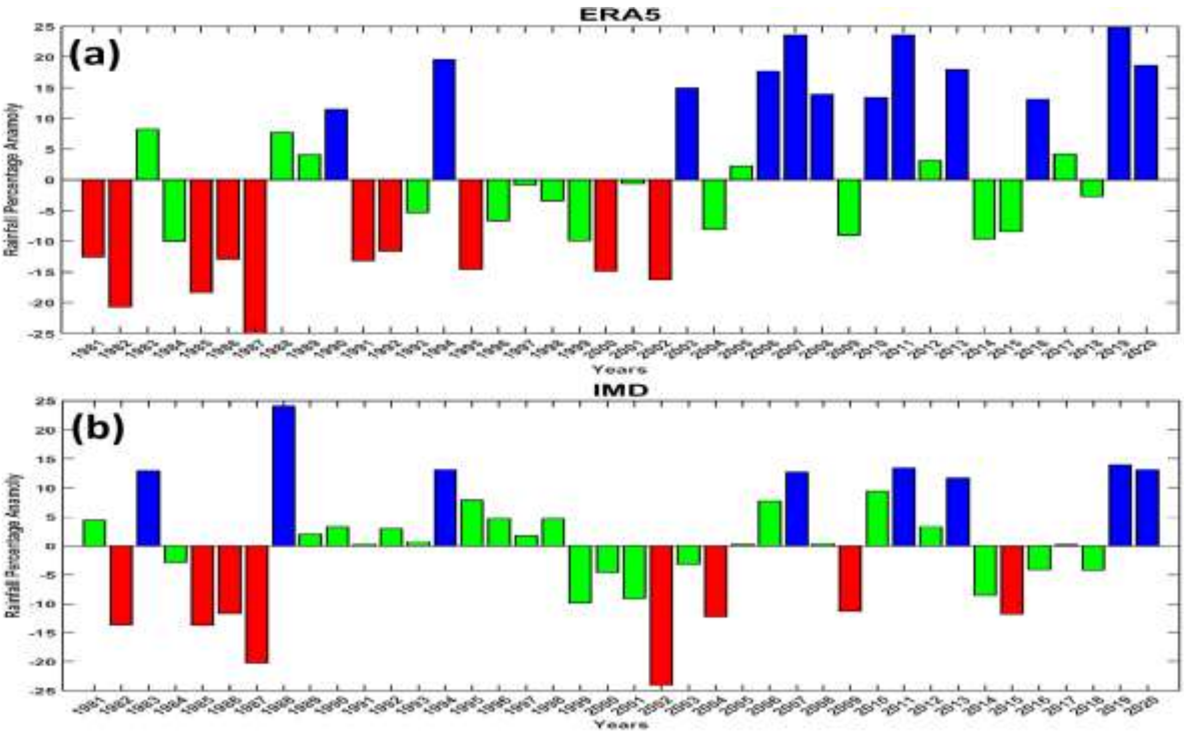

Figure 3: The percentage change in interannual rainfall from ERA5(a) and IMD(b) over the monsoon core zone

Table 3: Determination of IMD and ERA5 Surplus and Deficit Years for the Period 1981-2020

Surplus year (Common in IMD, ERA5)	Deficit year (Common in IMD, ERA5)
2007, 2011, 2013, 2019, 2020	1982, 1985, 1986, 1987,2002

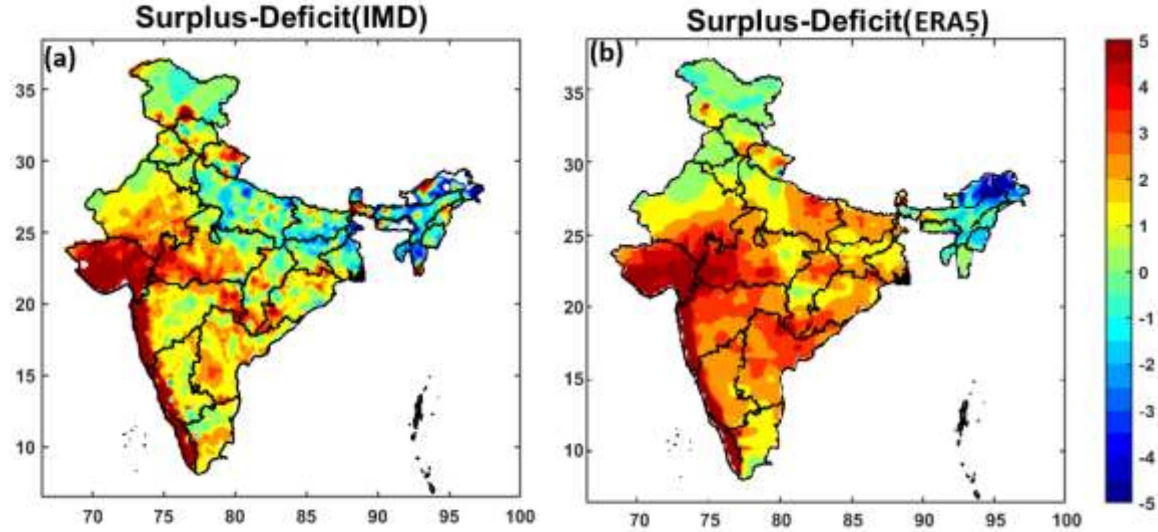

Figure 4: Composite of five years' worth of rainfall (mm/day) of Surplus-Deficit ERA5(a) ERA5(b)

4.2 Semipermanent Features' Characteristics in Surplus and Deficit Years

(A) Somali Jet: The Somali jet, a low-level atmospheric circulation, manifests as a narrow corridor of strong winds over the Horn of Africa. Originating from the Indian Ocean, it peaks during the boreal summer, extending inland towards East Africa. Characterized by its seasonality and intermittent nature, this phenomenon brings moisture from the ocean, influencing the region's climate. Its distinctive traits include variability in strength and position, impacting local weather patterns and rainfall distribution. The Somali jet's significance lies in its role in driving the regional monsoon system, affecting agriculture, ecosystems, and socio-economic activities in East Africa, albeit with complexities in forecasting due to its dynamic behaviour.

The Somali Jet, a low-level airflow prevailing over the equatorial Indian Ocean during boreal summer, is instrumental in supplying a significant portion of moisture to the Indian monsoon. Originating near Madagascar between 10–20° S, this Jet extends southward into the southern hemisphere. As it progresses towards the equator along the African coast, its circulation intensifies, resulting in a westward shift in the zonal component. Upon reaching approximately 10°N near the Horn of Africa, the south-westerly flow peaks near the Somali coast. Traversing over the Arabian Sea and India, the Jet encounters a notable decrease in wind speeds upon reaching the western coast of India due to the barrier posed by the Western Ghats. The collision of moisture-laden winds from the Arabian Sea with the Western Ghats leads to the formation of intense orographic rain bands, primarily on the windward side of the mountains along the west coast of India. Continuing its path across peninsular India and Sri Lanka, the Jet encounters atmospheric obstruction caused by the Himalaya-Tibetan Plateau, resulting in moisture accumulation and heightened rainfall in the central Indian region and the foothills of the Himalayas. Moreover, localized heavy rainfall areas in northern India are attributed to the presence of the Himalayas (Boos and Kuang, 2010). The Jet's trajectory extends towards northeast India, contributing to high-intensity rainfall. Initial examination focuses on evaluating the position and intensity of the Jet during surplus and deficit rainfall years. Figures (a, b, c) depict the seasonal (June to September) mean wind vectors (illustrated by black arrows) and wind speeds (in m/s) (represented as contours) at the 850 hPa pressure level for both surplus and deficit years. In Figure 5(a), the Jet exhibits robust strength (wind speed >22 m/s) across a considerable expanse in Somalia, but its intensity diminishes as it approaches India's western coast, specifically the Western Ghats, during a surplus year. In contrast, Figure 5(b) illustrates that the Jet's intensity is comparatively weaker (wind speed >20 m/s) over a smaller area, decreasing as it nears the west coast of India, particularly the Western Ghats, during a deficit year. Furthermore, Figure 5(c) displays the anomaly between surplus and deficit years. Positive anomalies span across Somalia, the Arabian Sea, and the Indian peninsular area, signifying higher wind magnitudes during surplus years. Conversely, negative anomalies stretch from Rajasthan to parts of Maharashtra in central India, indicating reduced wind magnitudes during deficit years. The Somali Jet, a key component of the monsoon system, exhibits varying behaviours during surplus and deficient monsoon seasons. In surplus years, the Somali Jet tends to strengthen, contributing to intensified monsoon circulation and increased moisture transport towards the Indian subcontinent. This enhanced circulation pattern often correlates with above-average rainfall over the Indian monsoon core region. Conversely, during deficient monsoon seasons, the Somali Jet may weaken, leading to decreased moisture transport and reduced rainfall over the affected areas. Understanding the dynamics of the Somali Jet in surplus and deficient monsoon years is essential for predicting and managing the impacts of monsoon variability on regional climate and agriculture.

The Indian monsoon is a complex meteorological phenomenon crucial for the agriculture-dependent economies of South Asia. Recent studies have highlighted the role of various atmospheric components in modulating monsoon behaviour. Among these, the Somali Jet—a narrow band of strong westerly winds—has gained attention for its potential influence on the Indian monsoon system. This research aims to elucidate the relationship between the Somali Jet and the Indian monsoon, shedding light on its implications for regional climate dynamics. Our findings reveal significant correlations between the intensity and position of the Somali Jet and the onset, duration, and spatial distribution of the Indian monsoon. We observe that during active phases of the monsoon, the Somali Jet strengthens and shifts northward, enhancing moisture transport towards the Indian subcontinent. Conversely, weakened Somali Jet during monsoon breaks corresponds to suppressed rainfall over the region. This study underscores the intricate linkages between the Somali Jet and the Indian monsoon system, emphasizing the former's role as a potential modulator of monsoon variability. Improved understanding of this relationship can enhance seasonal forecasting efforts and facilitate better management of water resources and agricultural practices in South Asia, ultimately contributing to socio-economic resilience in the region. Further research is warranted to explore the underlying mechanisms driving these interactions and their implications for future climate scenarios.

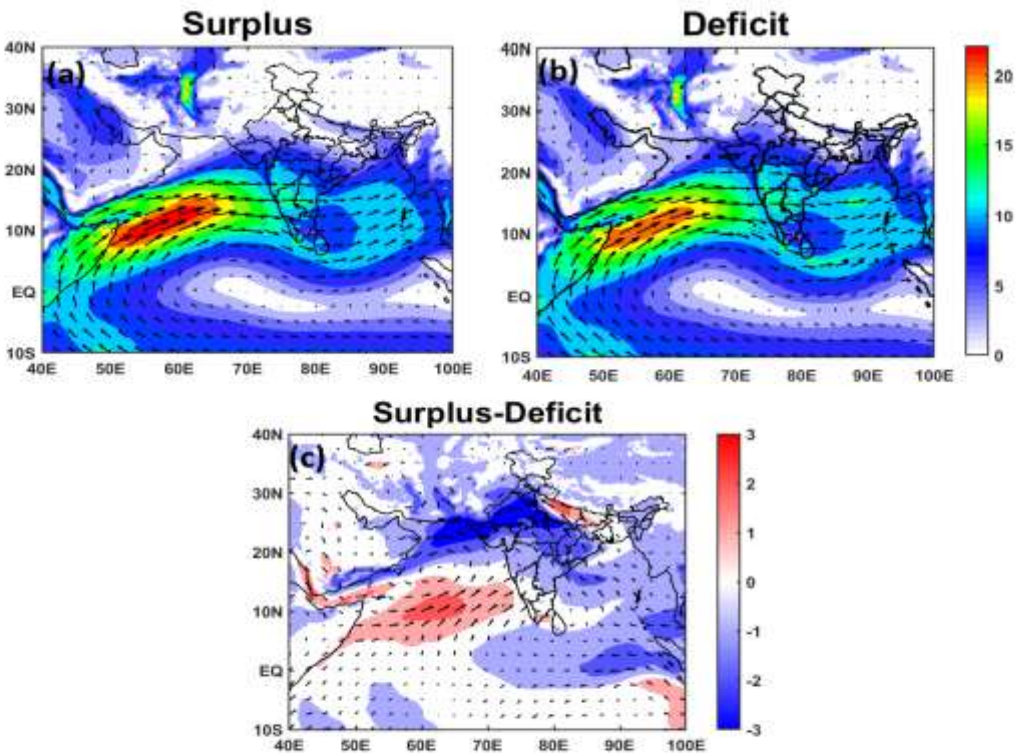

Figure 5 ERA5 composite shows five years of surplus (a), deficit (b), and surplus-deficit (c), respectively. The vector indicates the direction of the wind and the color bar and contour indicate the wind magnitude (m/s).

(B) Monsoon Trough: The Indian monsoon, a vital component of the regional climate system, is characterized by the presence of various atmospheric features, among which the monsoon trough holds significant importance. This research aims to delve into the dynamics of the monsoon trough within the Indian monsoon system, elucidating its role in modulating rainfall patterns and seasonal variability. Our study unveils the prominent influence of the monsoon trough on the Indian monsoon, showcasing its association with the onset, progression, and withdrawal phases of the seasonal rainfall. We observe a strong correlation between the position and intensity of the monsoon trough and the spatial distribution of precipitation across the Indian subcontinent. Moreover, the monsoon trough exhibits distinct features during active and break phases of the monsoon, indicating its role in modulating monsoon variability. The findings underscore the significance of the monsoon trough as a key determinant of monsoon dynamics in the Indian region. Enhanced understanding of its behavior can lead to improved seasonal forecasting and early warning systems, benefiting various sectors such as agriculture, water resource management, and disaster preparedness. Further research focusing on the intricate interactions between the monsoon trough and other atmospheric phenomena is essential for advancing our knowledge of the Indian monsoon system and its implications for climate resilience and adaptation strategies. According to studies by Wang (2006), Narasimha et al. (1997), and Krishnamurti and Surgi (1987), the monsoon trough (MT) is a notable and persistent area of low pressure that extends from the Bay of Bengal to the central Indian and Gangetic plains in northern India. The Monsoon Trough represents a pivotal atmospheric feature crucial in shaping the wet season across various tropical regions worldwide. It manifests as an elongated area of low pressure, typically stretching from the Western Pacific Ocean to the Indian Ocean, and can extend over continents like Asia and Africa. Characterized by its shifting nature in response to seasonal changes, the trough serves as a convergence zone where moisture-laden winds from different directions converge, fostering the development of thunderstorms and widespread rainfall. Its position fluctuates based on the migration of the Intertropical Convergence Zone (ITCZ) and the movement of high-pressure systems. The Monsoon Trough's significance lies in its role as a catalyst for the monsoon rains, critical for agriculture, hydrology, and ecosystems in affected regions. Understanding its behavior and variability aids meteorologists in forecasting rainfall patterns, mitigating risks associated with floods or droughts, and managing water resources for communities reliant on monsoon-driven precipitation.

The east-west-oriented Monsoon Trough (MT) significantly influences the Indian subcontinent's monsoon dynamics, dictating the active and break cycles, and consequently, the seasonal and interannual rainfall variability. Stretching from the Bay of Bengal to Rajasthan across Central India, this oscillating feature impacts regional rainfall patterns. Its southward movement fosters substantial rains in Peninsular India and southern Kenya, while its northward shift brings abundant rainfall to Northeast India. Incorporating the monsoon circulation and Intertropical Convergence Zone (ITCZ), the MT correlates with the low-pressure zones created by intensified insolation over the Tropic of Cancer. Greater evaporation and cloud formation result, affecting Outgoing Longwave Radiation (OLR) values. Surplus years exhibit higher OLR values (>185 W/m^2) from central India to Myanmar, indicating reduced convection and rainfall, contrasting with deficit years (<175 W/m^2) characterized by increased convection and heavier rainfall from Myanmar to Rajasthan, highlighting the MT's impact on rainfall distribution and intensity variations between surplus and deficit years. In Figure 6(c) depicting Surplus-Deficit years, the western sector of India and the Monsoon Core Zone (MCZ) exhibit negative Outgoing Longwave Radiation (OLR) anomaly values, whereas the eastern region of India and the MCZ portray positive OLR anomaly values. This signifies that higher negative OLR anomalies correspond to increased convection, leading to higher rainfall, whereas higher positive OLR anomalies indicate reduced convection, resulting in decreased rainfall. Consequently, heightened convection predominantly occurs in the central and western parts of India during surplus years, while a surplus of convection is observed in the eastern half of India during deficit years. The Monsoon Trough, a critical feature of the monsoon system, exhibits distinctive behaviours during surplus and deficient monsoon seasons. In surplus years, the Monsoon Trough tends to strengthen, extending further northwards and bringing increased rainfall activity across the Indian subcontinent. This intensified monsoon circulation pattern correlates with above-average precipitation and beneficial agricultural conditions. Conversely, during deficient monsoon seasons, the Monsoon Trough may weaken or shift southwards, resulting in decreased rainfall and potential drought conditions over the affected regions. Understanding the dynamics of the Monsoon Trough in surplus and deficient monsoon years is crucial for predicting and managing the socio-economic impacts of monsoon variability.

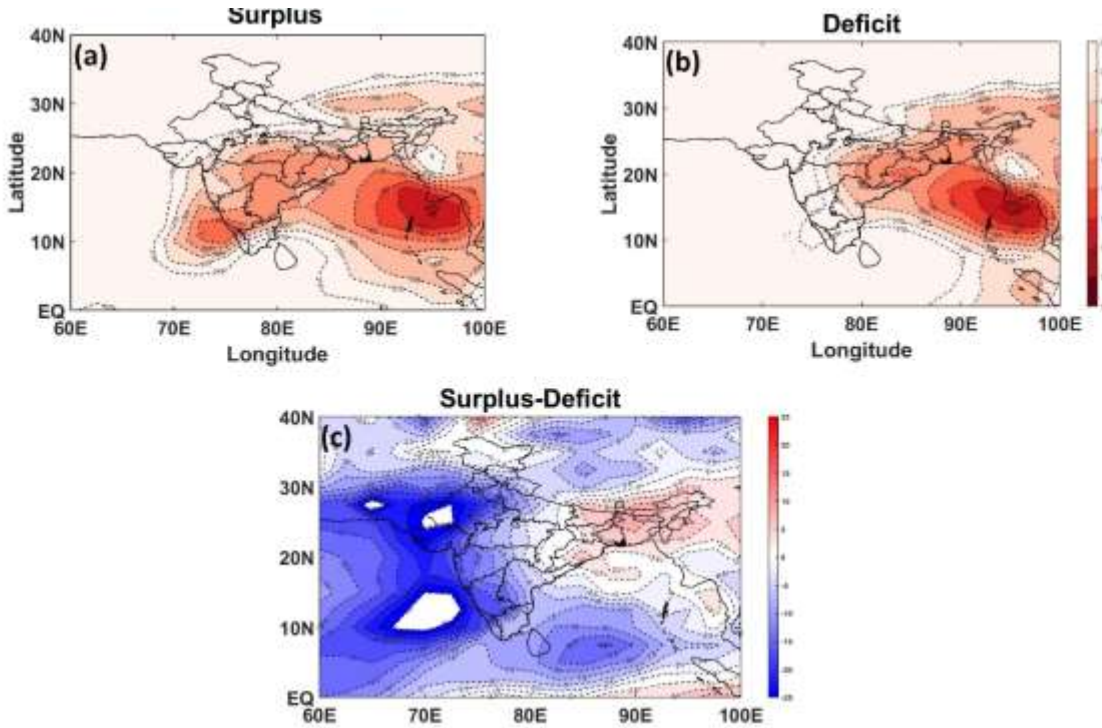

Figure 6. ERA5 composite shows the OLR(W/m2) as a color bar and contour for the five years of surplus(a), deficit(b), and surplus-deficit(c), respectively.

(C) TEJ: During summer in the northern hemisphere, the Tropical Easterly Jet (TEJ) is a prominent feature across southern Asia and northern Africa. It is usually visible between 5° and 20°N latitude. The TEJ is consistent in direction and intensity from June until early October, although its latitude varies by 5 to 20 degrees north. The TEJ crosses peninsular India and northern Africa, running from east to west and ranging in width from 6 to 9 kilometers. The establishment of the Tropical Easterly Jet (TEJ) initiates a reversal in the upper air circulation patterns, transitioning from high-pressure systems to low-pressure systems, consequently hastening the onset of monsoons. The Tropical Easterly Jet (TEJ) constitutes a crucial component of the atmospheric circulation system in tropical regions. This high-altitude zonal wind flow, prevalent during the summer monsoon season, extends across the tropical belt, typically between 10 to 20 degrees north in the Northern Hemisphere. The scope of studying the TEJ encompasses investigating its spatiotemporal variability, vertical structure, and interannual changes, essential in understanding monsoon dynamics. Research delves into the TEJ's influence on regional climate patterns, such as rainfall distribution, temperature anomalies, and weather extremes. Additionally, exploring its interaction with other atmospheric phenomena, like the Madden-Julian Oscillation (MJO) or El Niño-Southern Oscillation (ENSO), aids in predicting its behaviour and its implications on agriculture, water resources, and societal impacts. Enhanced comprehension of the TEJ supports improved monsoon forecasts, assists in mitigating weather-related risks, and informs adaptation strategies for communities reliant on monsoon-driven precipitation.

Recent research indicates a direct correlation between the quantity of rainfall experienced in India during monsoons and the intensity as well as the duration of heating occurring on the Tibetan Plateau. During the monsoon season, the TEJ manifests in the upper troposphere and has been the subject of analysis aimed at comprehending its variability and its impact on both surplus and deficit phases of the monsoon cycle. Typically, the Tropical Easterly Jet (TEJ) is characterized by easterly winds observed within the 5–20° N latitude range at 200 hPa. Its core region typically resides west of southern India, positioned over the Arabian Sea, with wind speeds exceeding 22 m/s across a wide area, thereby enhancing the Indian monsoon (see Figure 7a). In surplus years, robust anticyclonic circulation prevails in higher latitudes, accompanied by larger wind vectors indicating intensified wind activity. Conversely, during deficit years (Figure 7b), the TEJ's core is still positioned over the Arabian Sea west of southern India, with wind speeds exceeding 22 m/s, but covering a narrower area, hence less effective in bolstering the Indian monsoon. Deficit years also exhibit strong anticyclonic circulation in higher latitudes, with diminished wind vectors suggesting reduced wind intensity. The (Surplus-Deficit) year depicted in Figure 7c shows a positive wind anomaly across central India, spanning from 20N to 30N from east to west. Additionally, a significantly larger positive anomaly occurs in the western sector of the Arabian Sea, exceeding 3 m/s. Meanwhile, a negative anomaly is evident in the southern section of the Bay of Bengal. The Tropical Easterly Jet, a significant component of the monsoon system, exhibits varying characteristics during surplus and deficient monsoon seasons. In surplus years, the Tropical Easterly Jet tends to strengthen, facilitating the transport of moisture-laden air from the Indian Ocean towards the Indian subcontinent. This strengthened jet stream contributes to enhanced monsoon rainfall and favourable agricultural conditions. Conversely, during deficient monsoon seasons, the Tropical Easterly Jet may weaken or shift, resulting in reduced moisture transport and decreased rainfall over affected regions. Understanding the behaviour of the Tropical Easterly Jet in surplus and deficient monsoon years is essential for forecasting and managing the impacts of monsoon variability.

The Indian monsoon, a complex phenomenon crucial for the socio-economic well-being of South Asia, is influenced by various atmospheric components. Among these, the Tropical Easterly Jet (TEJ) stands out for its potential impact on monsoon dynamics. This research aims to explore the characteristics and significance of the TEJ within the Indian monsoon system. Our study reveals the distinct characteristics of the TEJ, including its seasonal variability, strength, and spatial extent. We observe a close relationship between the TEJ and the Indian monsoon, with variations in TEJ intensity and position influencing monsoon onset, duration, and intraseasonal fluctuations. Furthermore, the TEJ acts as a conduit for moisture transport from the Bay of Bengal and Arabian Sea, impacting regional rainfall distribution. The findings highlight the importance of the TEJ as a key component of the Indian monsoon system. Understanding its behavior and interactions with other atmospheric phenomena is essential for enhancing monsoon prediction capabilities and informing adaptation strategies in sectors such as agriculture, water resource management, and disaster preparedness. Further research focusing on the underlying mechanisms driving TEJ variability is warranted to improve our understanding of its role in shaping monsoon dynamics and its implications for regional climate resilience.

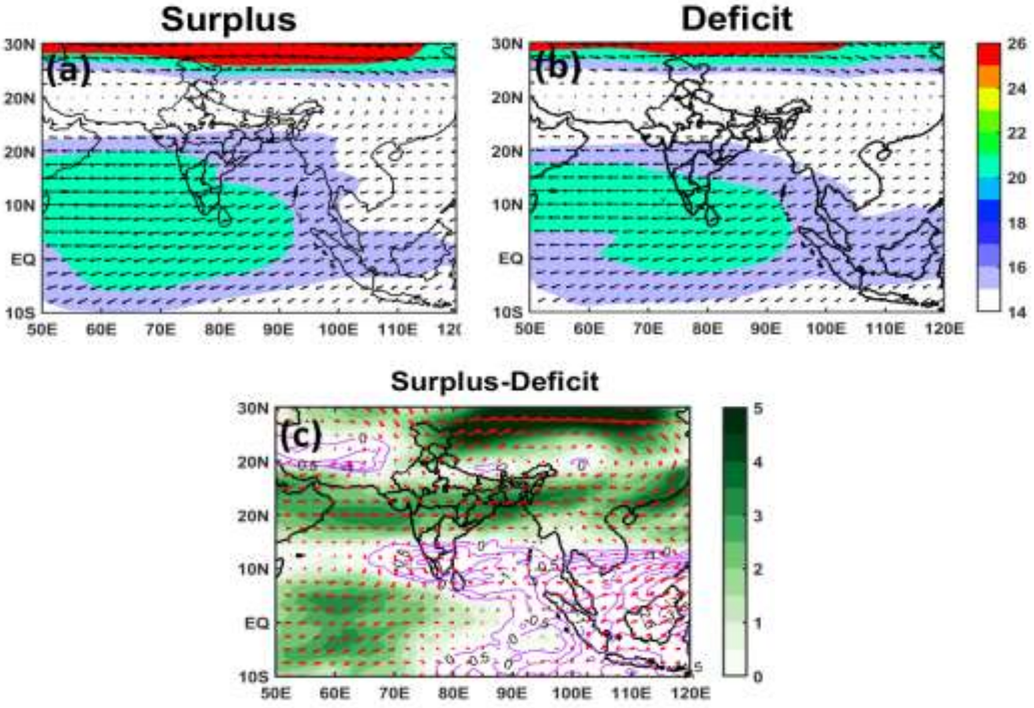

Figure 7. ERA5 composite shows five years of surplus (a), deficit (b), and surplus-deficit (c), respectively. The contour and color bar indicate the negative and positive anomalies of the wind's magnitude (m/s) and direction, respectively.

(D) Mascarene High: Located roughly between 20°S and 40°S and 45°E and 100°E, close to the Mascarene Islands in the Southern Indian Ocean (SIO), the Mascarene High (MH) is a high-pressure zone that is also known as the Indian Ocean subtropical high. The interhemispheric circulation that links the northern hemisphere's landmass to the Indian Ocean is influenced by this atmospheric phenomenon. This high-pressure system strengthens during the boreal summer, while at the same time, a low-pressure area develops in the northern hemisphere as a result of the subcontinental landmass being intensely heated by the sun. A semi-permanent subtropical anticyclone, the Mascarene High is situated in the southwest Indian Ocean. Positioned between Madagascar and Mauritius, it influences regional weather patterns and climate dynamics. Characterized by its seasonal variability, this high-pressure system intensifies during the austral winter, promoting stable, dry conditions. Conversely, during summer, it weakens, allowing for increased convective activity and rainfall. The Mascarene High significantly impacts the Indian Ocean's circulation, steering wind patterns, and influencing the trajectory of weather systems, including tropical cyclones. Understanding its behavior is crucial for weather prediction, as it modulates rainfall distribution, affects agricultural activities, and plays a pivotal role in shaping the climatic conditions of surrounding islands and coastal regions.

Due to the strong pressure gradient this produces between the northern and southern hemispheres, these regions are connected by a cross-equatorial wind pattern, which in turn supports a strong oceanic monsoon current that flows over the Arabian Sea. A vital link between the Indian monsoon trough and the Mascarene High (MH) is created by the anticyclonic circulation linked to the MH and its interconnected cross-equatorial winds, which carry moisture from the Southern Indian Ocean (SIO) to South Asia (Figure 8a). This connection profoundly influences the onset of the monsoon in India and precipitation patterns in East Asia. In surplus years, as shown in Figure 8, a high-pressure area is observed within the range of 20°S–40°S and 45°E–100°E, accompanied by anticyclonic circulation indicated by wind vectors. This circulation pattern is a consequence of the migratory low-pressure system off the coast of South Africa. The contours illustrate a wind magnitude of 2m/s at the center of the high-pressure zone, exhibiting an anticlockwise circulation pattern due to the influence of the migratory low-pressure system along the South African coast, albeit with reduced strength. Conversely, in a deficit year, observations reveal an increased strength in high-pressure areas, concentrated within a smaller zone with pressures exceeding 1028 hPa, as depicted in Figure 8b. The wind vector depicts larger magnitudes, indicating higher wind speeds (> 2 m/s) compared to a surplus year. Additionally, the anticlockwise circulation pattern appears notably stronger. These observations suggest a diminishing strength of the Mascarene High in the context of an escalating climate change scenario. Moving to Figure 12c, representing the (Surplus-Deficit) year, negative anomalies are evident in the vicinity of Madagascar, spanning across the Indian Ocean and the Arabian Sea within the latitude range of 45E-75E and longitude 10N-40S. This signifies high-pressure occurrences in deficit years and low-pressure patterns in surplus years. Conversely, a positive anomaly is observed in the Northern Indian continental region. The Mascarene High, an atmospheric high-pressure system over the southwest Indian Ocean, plays a crucial role in modulating the behaviour of the monsoon system during both surplus and deficient monsoon seasons. In surplus monsoon years, the Mascarene High tends to intensify, leading to strengthened atmospheric circulation patterns. This intensified high-pressure system influences the movement of air masses, facilitating the convergence of moisture-laden winds towards the Indian subcontinent. Consequently, surplus monsoon seasons often coincide with above-average rainfall and favourable agricultural conditions across the region. Conversely, during deficient monsoon seasons, the Mascarene High may weaken or shift position, impacting the circulation of air masses and moisture transport patterns. This weakening of the high-pressure system can disrupt the normal monsoon circulation, leading to reduced rainfall and potential drought conditions over affected areas. Additionally, changes in the intensity or position of the Mascarene High can influence the formation and movement of weather systems, further exacerbating the variability of monsoon rainfall. Understanding the dynamics of the Mascarene High in surplus and deficient monsoon years is essential for forecasting and mitigating the socio-economic impacts of monsoon variability. Through improved understanding and prediction of the Mascarene High's behaviour, stakeholders can better prepare for and manage the consequences of surplus and deficient monsoon seasons on agriculture, water resources, and socio-economic development.

The Indian monsoon, a vital climatic phenomenon for the Indian subcontinent, is influenced by various atmospheric features. Among these, the Mascarene High, a semi-permanent anticyclone over the southwest Indian Ocean, plays a significant role in modulating the Indian monsoon. This research aims to investigate the characteristics and impact of the Mascarene High on the Indian monsoon system. Our findings reveal the pronounced influence of the Mascarene High on the Indian monsoon, particularly during the summer monsoon season. The position and intensity of the Mascarene High influence the strength and spatial distribution of the monsoon rainfall, with variations in its characteristics impacting monsoon onset, duration, and intraseasonal variability. Additionally, the Mascarene High serves as a steering mechanism for moisture-laden winds, influencing monsoon dynamics over the Indian subcontinent.

The research underscores the significance of the Mascarene High as a crucial component of the Indian monsoon system. Improved understanding of its behaviour and interactions with other atmospheric features is essential for enhancing monsoon prediction capabilities and informing climate adaptation strategies in the region. Further investigations into the underlying mechanisms driving the Mascarene High variability are warranted to advance our understanding of its role in shaping monsoon dynamics and its implications for regional climate resilience.

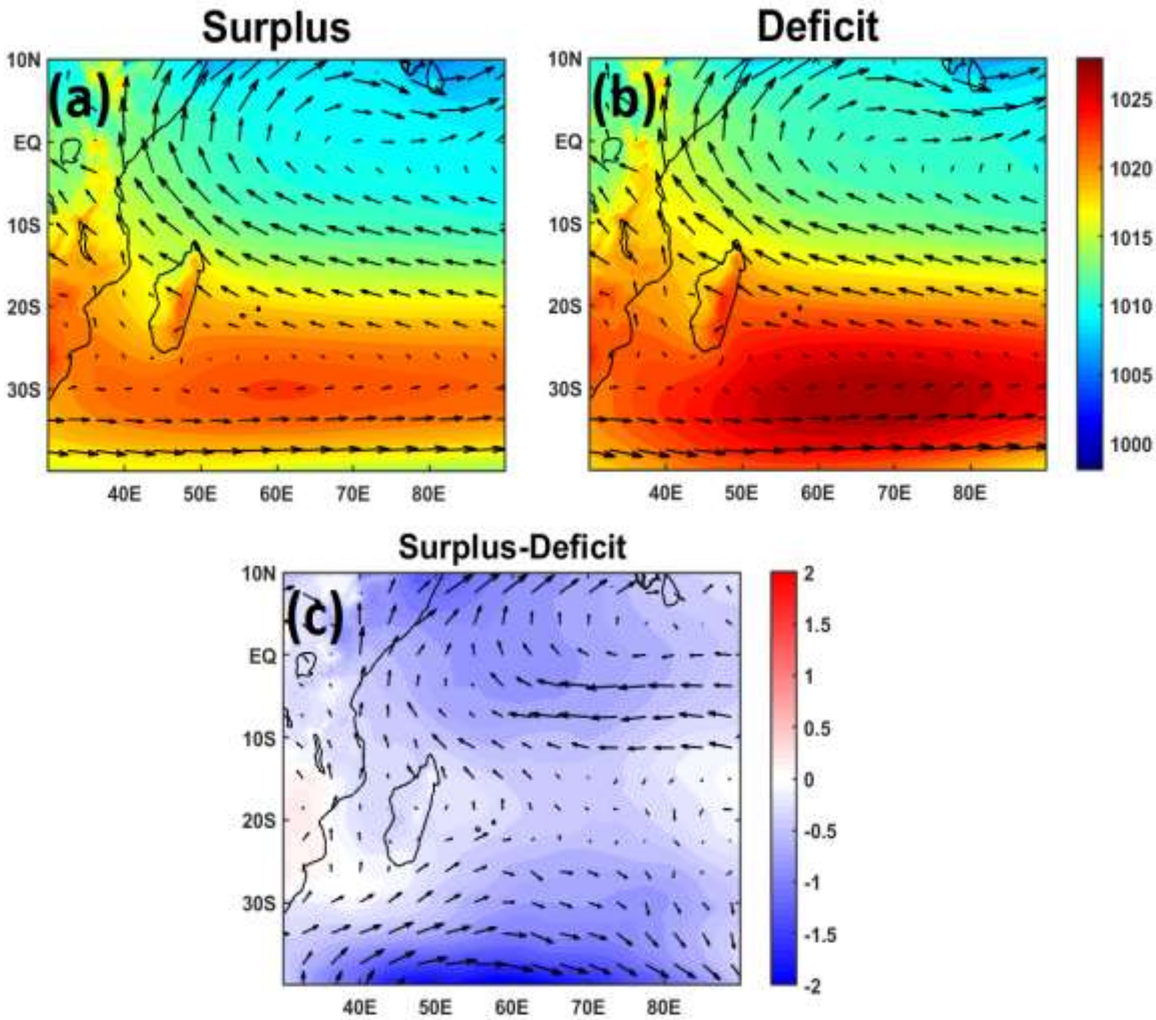

Figure 8. ERA5 composite shows five years of surplus (a), deficit (b), and surplus-deficit (c), respectively. The colorbar shows the mean sea level pressure (hPa), the contour shows the wind speed (m/s), and the vector shows the direction of the wind.

(E) Pakistan Heat Low: The Pakistan heat low persists from May to September, spanning across Pakistan and northwestern India, renowned as the ''heat low'' due to its dependence on surface heating. From May to July, a broad low-pressure system (1,002 hPa) stretches from the Arabian Sea to the Indian subcontinent, with the core of the Pak–India low at its lowest pressure contour (998 hPa). Situated over the Indus River plain and bordering the Hindu Kush mountain range to the west, it is illustrated in Figure 9 alongside Surface Air Temperature (SAT) and mean sea level pressure. Across Pakistan and northern India, an elongated low-pressure region showcases a distinct core, with SAT averaging 32°C over most of the subcontinent, rising to 34°C in southern Pakistan and the northwestern Rajasthan region. This low-pressure zone, marked by the closed 1002 hPa contour encircling its core, undergoes significant deepening, coinciding with the warmest SAT area (>34°C), indicating the profound influence of surface thermal dynamics on its intensification. In surplus years (Fig: 9a), the core deepens notably across southern Pakistan, central India, and the Indian peninsular region, fostering a low-pressure area at 1002 hPa. This stimulates the formation of low pressure across the Indian Subcontinent, enhancing the pressure gradient force and thus instigating the Indian summer monsoon. Conversely, in a deficit year (Fig: 9:b), coreless deepening occurs in the southern part of Pakistan and central India, alongside the Indian peninsular region where the pressure remains relatively high. In Figure 16c, representing the Surplus-Deficit year, a positive anomaly is evident over the Indian region, encompassing southern Pakistan, while a negative anomaly prevails over a small region in the southern part of Pakistan. The Pakistan Heat Low, a significant atmospheric feature, exhibits contrasting characteristics during surplus and deficient monsoon seasons, exerting profound influences on regional weather patterns and monsoon dynamics. In surplus monsoon years, the Pakistan Heat Low tends to strengthen, intensifying thermal contrasts and atmospheric instability over the region. This strengthened low-pressure system acts as a focal point for the convergence of moist air masses, enhancing monsoon rainfall across the Indian subcontinent and contributing to favourable agricultural conditions.

Conversely, during deficient monsoon seasons, the Pakistan Heat Low may weaken or shift, leading to reduced thermal contrasts and atmospheric instability. This weakening of the low-pressure system can disrupt the normal monsoon circulation, resulting in decreased moisture convergence and reduced rainfall over affected areas. The variability in the intensity and position of the Pakistan Heat Low can significantly impact monsoon rainfall patterns, influencing agricultural productivity, water resources availability, and socio-economic development in the region. Understanding the dynamics of the Pakistan Heat Low in surplus and deficient monsoon years is crucial for improving the prediction and management of monsoon variability. By elucidating the role of this atmospheric feature in modulating monsoon dynamics, researchers can enhance forecasting capabilities and develop strategies to mitigate the impacts of surplus and deficient monsoon seasons on various sectors, including agriculture, water management, and disaster preparedness. The Indian monsoon, a cornerstone of South Asia's climate, is influenced by various atmospheric phenomena, including the Pakistan Heat Low (PHL). This semi-permanent low-pressure system, situated over Pakistan during the summer months, plays a significant role in modulating monsoon dynamics. This research endeavours to unravel the characteristics and implications of the Pakistan Heat Low within the Indian monsoon system. Our findings reveal the substantial influence of the Pakistan Heat Low on the Indian monsoon, particularly over the north western region of the Indian subcontinent. The presence and intensity of the Pakistan Heat Low influence the spatial distribution and intensity of monsoon rainfall, with variations in its characteristics impacting monsoon onset, duration, and intraseasonal variability. Furthermore, the Pakistan Heat Low acts as a steering mechanism for moisture-laden winds, affecting monsoon circulation patterns and precipitation over the Indian landmass.

The research underscores the significance of the Pakistan Heat Low as a crucial component of the Indian monsoon system. Enhanced understanding of its behaviour and interactions with other atmospheric features is essential for improving monsoon prediction capabilities and informing climate adaptation strategies in the region. Further investigations into the underlying mechanisms driving Pakistan Heat Low variability are warranted to advance our understanding of its role in shaping monsoon dynamics and its implications for regional climate resilience.

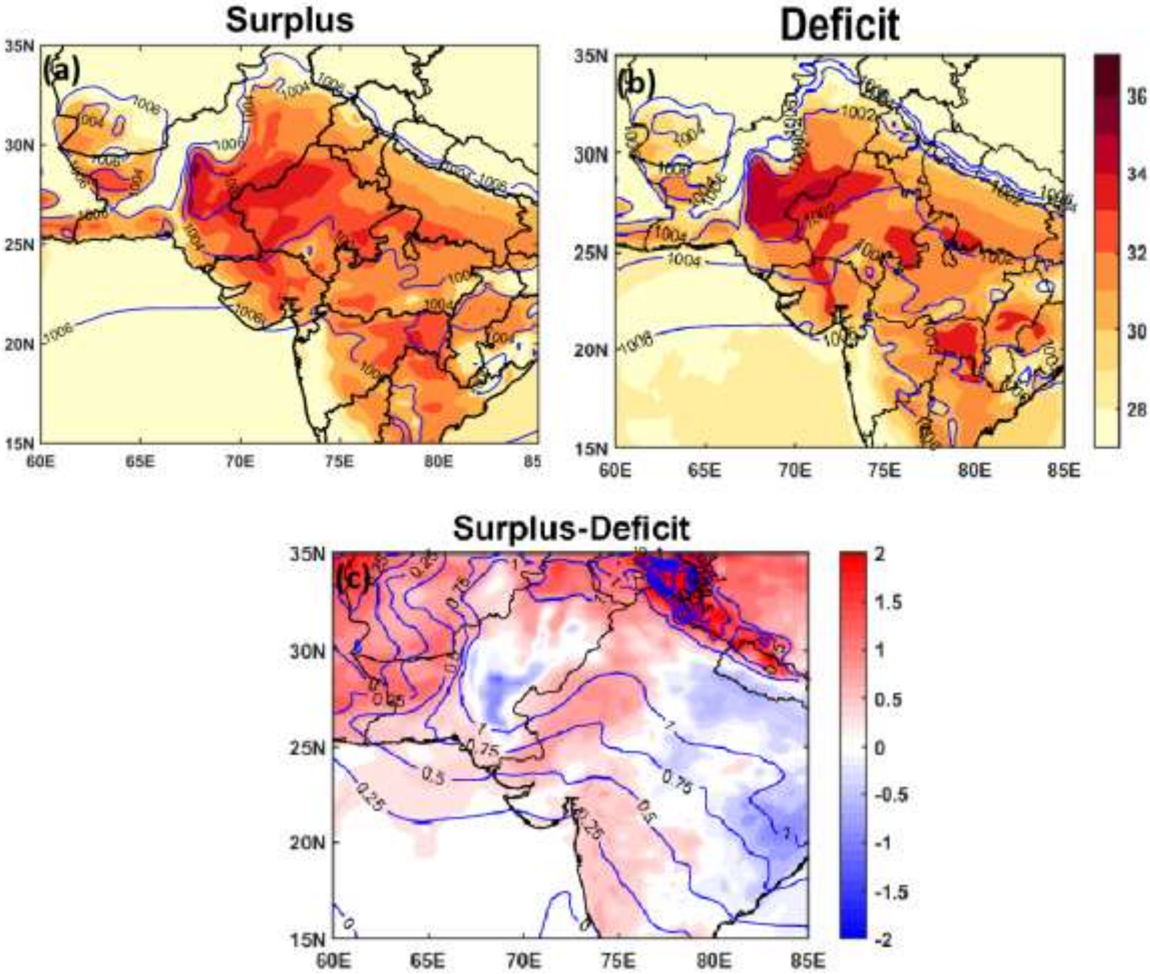

Figure: 9. ERA5 composite shows mean sea level pressure (hPa contours), surface air temperature (˚C, shaded), and five years of surplus (a), deficit (b), and surplus-deficit (c) years, respectively.

5: CMIP6 Projection:

5.1: Surplus, Deficit, Normal Year:

The Indian monsoon, a pivotal climatic phenomenon, exhibits considerable variability from year to year, leading to outcomes of surplus, deficit, or normal rainfall. Understanding the underlying factors governing these variations is crucial for mitigating the impacts of extreme weather events and optimizing resource management. This research aims to delve into the dynamics of surplus, deficit, and normal years in the Indian monsoon system. Several atmospheric and oceanic factors contribute to the variability of the Indian monsoon. These include the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Madden-Julian Oscillation (MJO), and the Tibetan Plateau's thermal contrast. The interaction of these factors influences the distribution of temperature, pressure, and moisture, ultimately shaping monsoon outcomes.

Surplus monsoon years are characterized by above-average rainfall, often leading to flooding and waterlogging in some regions. These years are typically associated with a weak or absent El Niño, a positive IOD, and favorable conditions in the Bay of Bengal. Increased moisture advection, enhanced convective activity, and a northward shift of the monsoon trough contribute to surplus rainfall during these years. Deficit monsoon years witness below-average rainfall, resulting in drought conditions, water scarcity, and agricultural losses. These years are often associated with El Niño events, negative IOD, and unfavorable conditions in the Bay of Bengal. Reduced moisture advection, weakened convective activity, and a southward shift of the monsoon trough contribute to deficient rainfall during these years.

Normal monsoon years exhibit rainfall within the average range, providing optimal conditions for agriculture and water resources. These years are characterized by a neutral ENSO phase, near-average IOD, and balanced atmospheric conditions in the Bay of Bengal. The monsoon trough maintains its typical position, and convective activity remains moderate, resulting in average rainfall distribution across the Indian subcontinent.

Surplus, deficit, and normal monsoon years have significant socio-economic implications, affecting agriculture, water resources, hydropower generation, and public health. To mitigate the impacts of extreme weather events, it is essential to enhance early warning systems, improve irrigation infrastructure, promote drought-resistant crops, and implement water conservation measures.

Understanding the mechanisms driving surplus, deficit, and normal years in the Indian monsoon system is essential for climate prediction, risk management, and sustainable development. Integrating multi-disciplinary research approaches and leveraging advanced modeling techniques can enhance our ability to forecast monsoon variability and develop adaptive strategies to minimize socio-economic vulnerabilities. Continued monitoring and research efforts are crucial for addressing the challenges posed by climate change and ensuring the resilience of communities dependent on the Indian monsoon.

Examining the Indian Summer Monsoon Rainfall (ISMR) involves analyzing raw data to compute rainfall percentage anomalies. This process utilizes datasets from IMD and ERA5, alongside various scenarios of CMIP6 rainfall data. The aim is to identify deficit and surplus years within SSP2.6(a), SSP4.5(b), SSP7.5(c), SSP8.5(d), IMD(e), and ERA5(f) for the monsoon core zone as indicated in Figure 10. This investigation specifically focuses on dissecting the rainfall patterns for distinct years marked by common deficits, such as 2018, and surpluses, like 2020, within the study area. The anomaly is calculated by subtracting the mean climatological value from the mean value of the respective year. This result is then divided by the mean climatological value, as depicted in Table 3. This table illustrates the common surplus and deficit years identified across various datasets. The rainfall percentage anomaly for deficit years in SSP4.5-ERA5(a) and SSP4.5-IMD(b) showcased in Figure 11(a-d) exhibits similar patterns. Underestimated rainfall is observed across the western Ghats and the Southern Peninsular region, encompassing portions of West Bengal, Jharkhand, and Uttar Pradesh. However, this discrepancy appears less prominent in SSP4.5-IMD (b). Conversely, overestimated rainfall is noticeable in Jammu and Kashmir, Maharashtra, and Chattisgarh, with SSP4.5-IMD (b) displaying a more intensified effect. In SSP8.5-ERA5(c), rainfall across the monsoon core zone is underestimated, although this disparity is more marked in SSP8.5-IMD (d). Both SSP4.5-IMD(e) and SSP4.5-ERA5(f) demonstrate a similar trend of underestimation in the entire southwest region and an overestimation in the Jammu and Kashmir region during normal years. SSP8.5-IMD(g) and SSP8.5-ERA5(h) both reveal a negative anomaly covering a smaller section of the Western Ghats and all Eastern regions such as Bihar, Jharkhand, and West Bengal. SSP8.5-ERA5(g) displays a more pronounced effect. Notably, SSP4.5 consistently indicates lower rainfall in the Western Ghats during both deficit and normal years, while SSP8.5 consistently reflects reduced rainfall in the Eastern part of India.

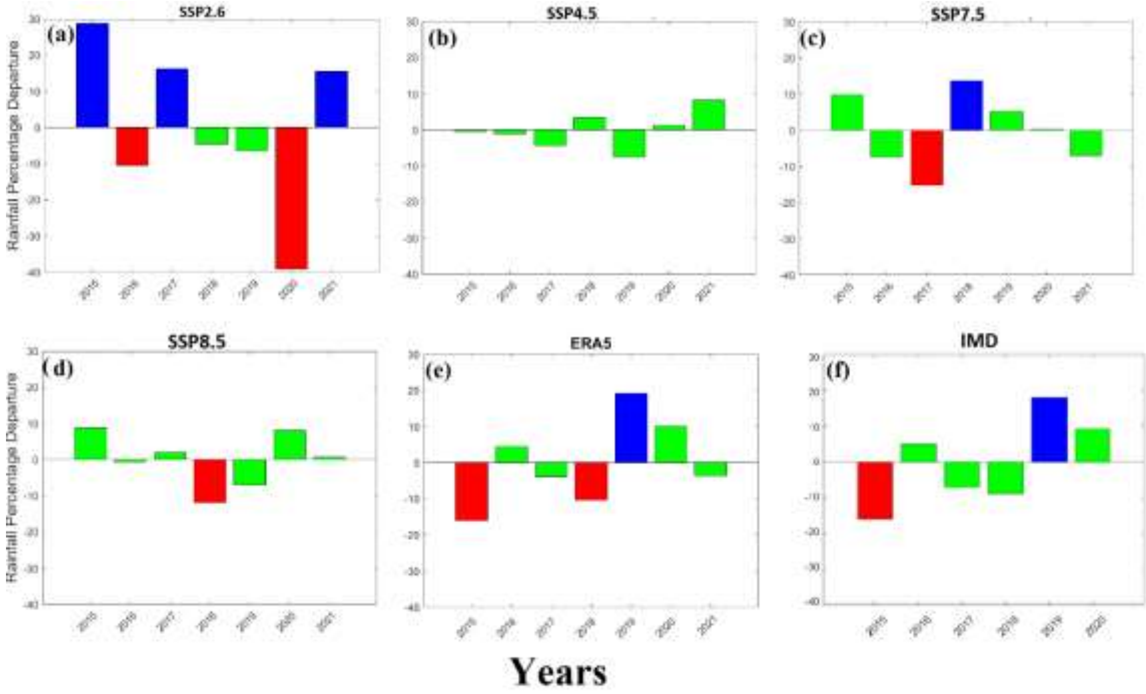

Figure 10: Bar plot of the % deviation in rainfall for several scenarios ERA5(e), IMD(f), SSP2.6(a), SSP4.5(b), SSP7.5(c), and SSP8.5(d).

Table:4 Identification of Surplus, Deficit, and Normal year in IMD, ERA5, SSP2.6, SSP4.5, SSP7.5, SSP8.5 for the time period 2015-2021

Deficit year (2018)	Surplus year (2019)	Normal Year (2020)
ERA5, IMD, SSP8.5, SSP2.6, SSP4.5	ERA5, IMD, SSP7.5	ERA5, IMD, SSP8.5, SSP7.5,SSP4.5

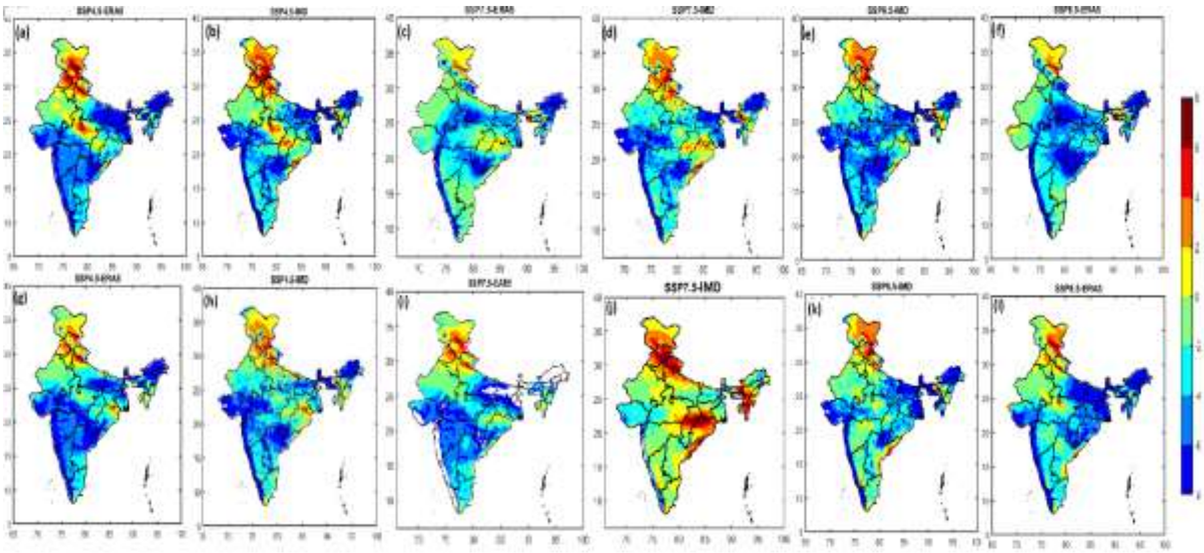

Figure 11. shows the difference between the mean rainfall of the ISMR in the Deficit year (2018) (above) and the Normal year (2020) (below), with the following SSP4.5-ERA5 values displayed in the above figure: SSP4.5-ERA5(a), SSP4.5-IMD(b), SSP7.5-ERA5(c), SSP7.5-IMD(d), SSP8.5-IMD(e), SSP4.5-ERA5(f), SSP4.5-ERA5(h), SSP7.5-IMD(i), SSP7.5-IMD(j), SSP8.5-IMD(k), and SSP8.5-ERA5(l).

5.2: Semipermanent Features' Characteristics in Surplus and Deficit Years with CMIP6 and ERA5:

(A) Somali Jet: The Indian monsoon, a complex atmospheric phenomenon, plays a pivotal role in the socio-economic fabric of South Asia. Among the various atmospheric features influencing the Indian monsoon, the Somali Jet, a narrow band of strong westerly winds over the Arabian Sea, has emerged as a significant driver of monsoon dynamics. This research aims to elucidate the characteristics and impacts of the Somali Jet within the Indian monsoon system. The Somali Jet is a prominent upper-level atmospheric circulation feature that extends from the eastern African coast across the Arabian Sea during the summer monsoon season. It typically develops in response to the temperature gradient between the African continent and the Indian Ocean, reaching its peak intensity during June-August. The Somali Jet is characterized by high wind speeds and serves as a conduit for moisture transport from the Arabian Sea towards the Indian subcontinent.

The Somali Jet exerts a profound influence on the Indian monsoon through various mechanisms. Firstly, it enhances moisture advection towards the Indian landmass, contributing to the intensification of rainfall over the western and central regions of the country. Secondly, the Somali Jet interacts with other atmospheric features such as the Tibetan Plateau and the Indian Ocean Dipole, modulating the strength and position of the monsoon trough and influencing the distribution of rainfall across the Indian subcontinent. Lastly, variations in the intensity and position of the Somali Jet can lead to intraseasonal fluctuations in monsoon rainfall, impacting agricultural activities and water resource management.

The Somali Jet exhibits interactions with key climate modes such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), further influencing monsoon variability. During El Niño events, the Somali Jet tends to weaken, resulting in suppressed monsoon rainfall over the Indian subcontinent. Conversely, positive phases of the IOD strengthen the Somali Jet, enhancing moisture transport and promoting above-average rainfall over parts of India. The Somali Jet plays a crucial role in shaping the spatiotemporal characteristics of the Indian monsoon. Enhanced understanding of its behaviour and interactions with other atmospheric and oceanic phenomena is essential for improving monsoon prediction capabilities and informing climate adaptation strategies in the region. Continued research efforts focusing on the dynamics of the Somali Jet are warranted to advance our understanding of its role within the Indian monsoon system and its implications for regional climate resilience.

Figure 12 portrays the comparison (a-c) between model simulations and ECMWF reanalysis, displaying the monthly mean wind at 850 hPa during the Boreal summer monsoon for both deficit and normal years (ERA5). In the reanalysis data, the Somali low-level jet over the Arabian Sea is accurately represented. However, in the simulated data of SSP4.5 (a) and SSP8.5 (b), the jet speeds of 14–16 m/s across the Arabian Sea seem underestimated compared to ERA5 values of 22 m/s in deficit years. Additionally, in SSP8.5, the wind speed is stronger in the central section of the Bay of Bengal (85E-100E, 5N-12N) at 10 m/s. This weaker wind across the Indian continent occurs because most of the wind is directed over the Bay of Bengal, which absorbs a greater amount of moisture. The south-westerly jet, observed at 20-22 m/s in ERA5, is an overestimation as shown in Figure 12(d-f). In normal years, SSP4.5(d) displays a stronger jet, while SSP8.5(e) demonstrates higher activity over the Arabian Sea region and the southern part of Sri Lanka (70E-90E, 5-7N), with less impact over the Indian continent. However, during deficit years, SSP8.5 exhibits a stronger jet compared to normal years. In deficit years, the Arabian Sea's jet is intensified compared to normal years, but more wind passes through the Bay of Bengal in deficit years, thereby limiting the moisture reaching the Indian continent. Consequently, a stronger jet is observed during deficit years. The Somali Jet, a significant component of the monsoon system, exhibits distinct behaviour during surplus and deficient monsoon seasons, exerting considerable influence on regional weather patterns and monsoon dynamics. In surplus monsoon years, the Somali Jet tends to strengthen, intensifying atmospheric circulation and moisture transport from the Indian Ocean towards the Indian subcontinent. This strengthened jet stream facilitates the convergence of moisture-laden air masses, leading to increased monsoon rainfall and favourable agricultural conditions across the region. Conversely, during deficient monsoon seasons, the Somali Jet may weaken or shift, resulting in reduced moisture transport and decreased rainfall over affected areas. The weakening of the jet stream can disrupt the normal monsoon circulation, leading to drought conditions and agricultural losses. The variability in the intensity and position of the Somali Jet plays a crucial role in modulating monsoon rainfall patterns, influencing agricultural productivity, water availability, and socio-economic development in the region. Understanding the dynamics of the Somali Jet in surplus and deficient monsoon years is essential for improving the prediction and management of monsoon variability. By elucidating the role of this atmospheric feature in monsoon dynamics, researchers can enhance forecasting capabilities and develop strategies to mitigate the impacts of surplus and deficient monsoon seasons on various sectors, including agriculture, water management, and disaster preparedness.

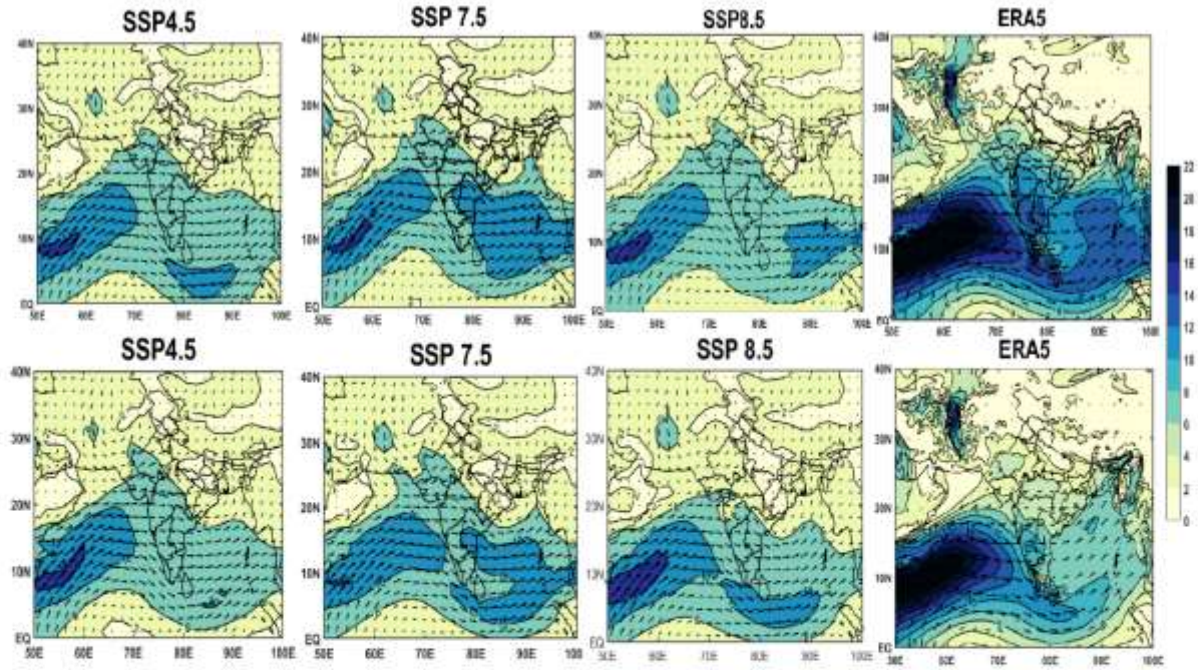

Fig:12 The picture illustrates the mean wind speed (ms−1) for the Deficit year (2018), which has SSP4.5(a), SSP7.5(b), SSP8.5(c), and ERA5(d), and the Normal year (2020), which has SSP4.5(e), SSP7.5(f), SSP8.5(g), and ERA5(h). The shaded colors represent the mean wind speed (ms−1) for each year.

(B) Mascarene High: The Indian monsoon, a vital climatic phenomenon for South Asia, is influenced by various atmospheric features. Among these, the Mascarene High, a semi-permanent anticyclone situated over the southwest Indian Ocean, plays a significant role in shaping monsoon dynamics. This research aims to explore the characteristics and implications of the Mascarene High within the Indian monsoon system. The Mascarene High is a high-pressure system located over the Mascarene Islands in the southwest Indian Ocean. It is characterized by its semi-permanent nature, with its position and intensity varying seasonally. During the summer monsoon season (June-September), the Mascarene High strengthens and extends eastward, influencing the atmospheric circulation patterns over the Indian Ocean region.

The Mascarene High exerts a notable influence on the Indian monsoon through several mechanisms. Firstly, it influences the strength and position of the subtropical westerly jet stream, which in turn affects the movement of weather systems over the Indian subcontinent. Secondly, the Mascarene High influences the advection of moisture from the Indian Ocean towards the Indian landmass, contributing to the intensification of rainfall during the monsoon season. Additionally, variations in the intensity and position of the Mascarene High can lead to changes in the strength and spatial distribution of the monsoon rainfall, impacting agricultural activities and water resource management. The Mascarene High exhibits interactions with key climate modes such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), further influencing monsoon variability. During El Niño events, the Mascarene High tends to weaken, resulting in suppressed monsoon rainfall over the Indian subcontinent. Conversely, positive phases of the IOD strengthen the Mascarene High, enhancing moisture transport and promoting above-average rainfall over parts of India. The Mascarene High plays a crucial role in shaping the spatiotemporal characteristics of the Indian monsoon. Enhanced understanding of its behaviour and interactions with other atmospheric and oceanic phenomena is essential for improving monsoon prediction capabilities and informing climate adaptation strategies in the region. Continued research efforts focusing on the dynamics of the Mascarene High are warranted to advance our understanding of its role within the Indian monsoon system and its implications for regional climate resilience.

The Mascarene High plays a pivotal role in the Indian Summer Monsoon (ISM) system. In Figure 13(a-c), during deficit years, the SSP4.5 projection (a) for the Mean Sea Level Pressure (MSLP) of the Mascarene high shows a low-pressure area (less than 1025hPa), indicating a failure to establish high pressure over the Madagascar region. In contrast, SSP8.5 (b) exhibits a high-pressure zone (higher than 1025hPa) spread across a larger area during deficit years, suggesting a stronger pressure gradient between the Southern Ocean and the Northern Continental portion. However, it doesn't precisely align with the benchmark of ERA5 (c) used for validation. In deficit years, SSP4.5 aligns closely with ERA5, but during normal years, SSP8.5 performs better. Comparing SSP4.5(d) with SSP8.5 and ERA5 in Figure 13(d-f), SSP4.5(d) portrays a significantly high-pressure zone during normal years, implying a broader area of high pressure in the future.

Conversely, SSP8.5 in normal years exhibits a pattern similar to ERA5, with reduced high-pressure areas that form concentric patterns. The predominant contribution of heat advection to the observed warming trend is highlighted by research on the mixed-layer heat budget. Stronger zonal currents carry warm waters from the Western Pacific (WP) to the Mascarene High (MH) region during this warming phase. As a result of warming, the sea level pressure in the MH drops, resulting in a small pressure differential between the MH and the northern hemisphere's continent. As a result of this pressure shift, the cross-equatorial winds in the western Indian Ocean become weaker.

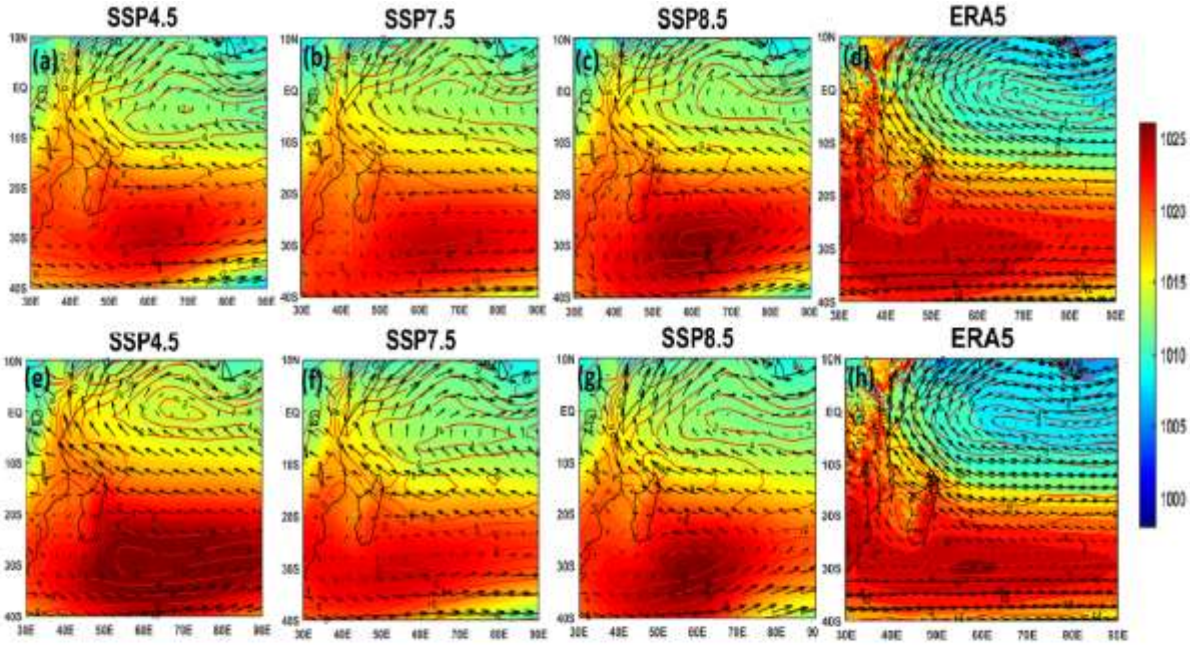

Fig:13 The mean sea level pressure in the Deficit year (SSP4.5(a), SSP7.5(b), SSP8.5(c), and ERA5(d) and in the Normal year (2020) (SSP4.5(e), SSP7.5(f), SSP8.5(g), and ERA5(h)) are depicted in the above figure, respectively, with shaded colors and mean JJAS winds (ms−1) at 850 hPa.

(C) Tropical Easterly Jet: The Indian monsoon, a complex atmospheric phenomenon crucial for South Asia, is governed by various atmospheric features. Among these, the Tropical Easterly Jet (TEJ) holds significance for its role in modulating monsoon dynamics. This research aims to elucidate the characteristics and impacts of the TEJ within the Indian monsoon system. The TEJ is a narrow, high-speed wind belt located at upper levels of the atmosphere, typically around 200-300 hPa, extending across the Indian subcontinent during the summer monsoon season (June-September). It is formed as a result of the temperature gradient between the Indian Ocean and the Tibetan Plateau and is influenced by the position of the Inter-Tropical Convergence Zone (ITCZ) and the subtropical westerly jet stream. The TEJ plays a crucial role in shaping the Indian monsoon through various mechanisms. Firstly, it facilitates the transport of moisture from the Bay of Bengal and the Arabian Sea towards the Indian landmass, thereby enhancing convective activity and promoting rainfall. Secondly, the TEJ interacts with other atmospheric features such as the monsoon trough, influencing its position and intensity and thereby modulating the distribution of monsoon rainfall across the Indian subcontinent. Additionally, variations in the intensity and position of the TEJ can lead to intraseasonal fluctuations in monsoon rainfall, impacting agricultural activities and water resource management.

The TEJ exhibits interactions with key climate modes such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), further influencing monsoon variability. During El Niño events, the TEJ tends to weaken, resulting in suppressed monsoon rainfall over the Indian subcontinent. Conversely, positive phases of the IOD strengthen the TEJ, enhancing moisture transport and promoting above-average rainfall over parts of India. The Tropical Easterly Jet plays a crucial role in shaping the spatiotemporal characteristics of the Indian monsoon. Enhanced understanding of its behaviour and interactions with other atmospheric and oceanic phenomena is essential for improving monsoon prediction capabilities and informing climate adaptation strategies in the region. Continued research efforts focusing on the dynamics of the TEJ are warranted to advance our understanding of its role within the Indian monsoon system and its implications for regional climate resilience.

Figure 14 (a-c) highlights this observation: In SSP4.5(a), the Tropical Easterly Jet (TEJ) appears weaker during deficit years but stronger during normal years, offering insights into the Monsoon dynamics. In SSP8.5(b), the TEJ is weaker in deficit years (Fig:14b) and stronger in regular years (Fig 14:d), indicating a stronger Monsoon during normal years. Both scenarios align well with ERA5. The circulation is less robust in SSP8.5 during deficit years and stronger in normal years. Notably, a La Niño event can enhance the TEJ, while an El Niño event can attenuate it. A more potent jet at higher latitudes coupled with strong southwest to west winds at lower latitudes suggests a more vigorous monsoon circulation. Figure 14 (d-f) in SSP8.5(b) demonstrates that the intensity is relatively weaker over the Southwest region during normal years and is underestimated compared to ERA5 (c).

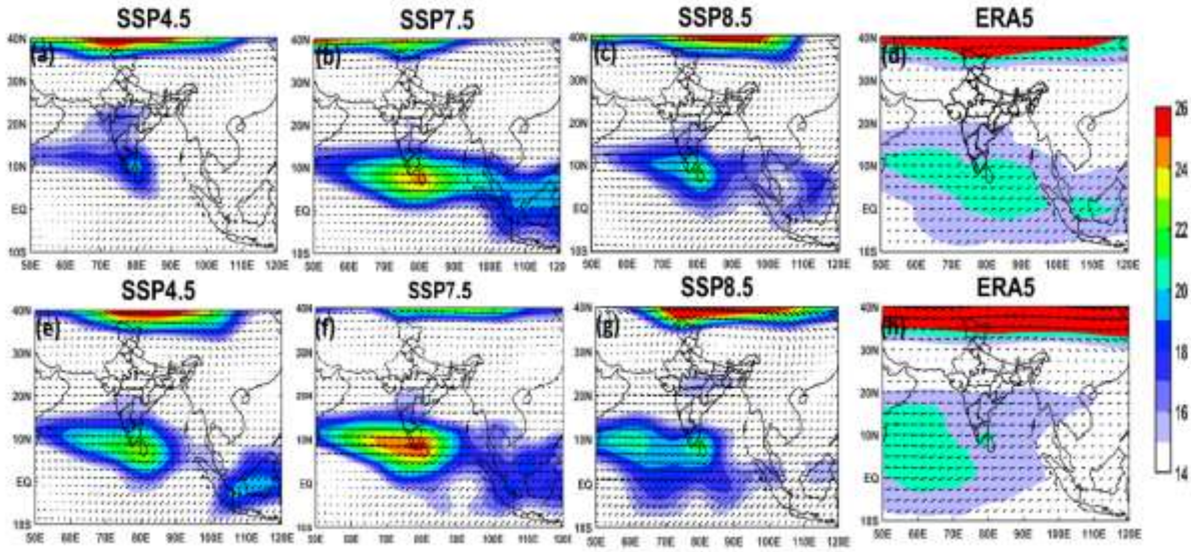

Fig.14 Mean JJAS winds (ms−1) at 200 hPa and shaded color represent the mean wind speed (ms−1) in the Normal year (2020) with SSP4.5(e), SSP7.5(f), SSP8.5(g), and ERA5(h) depicted in above figure, and in the Deficit year (2018) with SSP4.5(a), SSP7.5(b), SSP8.5(c), and ERA5(d).

6: Conclusions

This research delves into the intricate dynamics of monsoon systems and their evolving traits in the context of climate change, focusing on their environmental implications. Examining the shifting patterns of monsoon semi-permanent traits, the study investigates their profound impacts on ecosystems, agriculture, water resources, and biodiversity. Through meticulous analysis of climatic variables and ecological stability, it elucidates the interplay between changing monsoon characteristics and environmental dynamics. The study aims to offer comprehensive insights into how altered monsoon traits influence regional and global climates. By elucidating the connections between monsoon traits and environmental consequences, this research provides a nuanced understanding crucial for adaptive strategies, policy formulation, and mitigation efforts in the face of ongoing climate change. We utilized ERA5 and IMD data spanning from 1981 to 2020 to identify 10 deficit and 12 surplus years (ERA5) and 8 deficit and 8 surplus years (IMD), determining rainfall percentage departures. Focusing on 5 common surplus and 5 common deficit years, distinctive behaviors within the Monsoon Surplus Features (MSF) emerged. Surplus years exhibited a stronger Somali Jet, reaching 22m/s across a larger area, suggesting enhanced moisture transport towards the Indian subcontinent compared to deficit years. Analysis of the Mascarene high showcased lower mean sea level pressure during surplus and higher pressure during deficit years, possibly attributed to temporal differences. Changes in the western Pacific due to the Indonesian Throughflow might contribute to these variations. The Tropical Easterly Jet strengthened over the Arabian Sea in surplus years, reinforcing the Indian monsoon with robust circulation. Land surface and sensible heating deepened the Pak–India low, crucial for triggering the Indian summer monsoon. Comparing surplus and deficit years revealed positive anomalies over the Western Ghats and northwestern India, amplifying monsoon triggers via pronounced pressure gradients. In the Monsoon trough, lower Outgoing Longwave Radiation (OLR) during surplus years indicated intensified convection, higher rainfall, contrasting with higher OLR in deficit years, denoting reduced convection and cloudiness.

The provided passage discusses the analysis of rainfall anomaly departures under various scenarios, including Shared Socioeconomic Pathways (SSP) 2.6, 4.5, 7.5, and 8.5, as well as observational datasets from the Indian Meteorological Department (IMD) and the ERA5 reanalysis dataset. These analyses offer valuable insights into projected rainfall patterns and their deviations from historical norms. The comparison between SSP4.5-IMD and SSP4.5-ERA5 highlights discrepancies in projected rainfall amounts, particularly in regions like Chattisgarh and Madhya Pradesh. The overestimation of rainfall in these areas under SSP4.5 suggests potential biases in the climate model, which could impact water resource management and agricultural planning. In deficit years, SSP8.5-IMD indicates underestimated rainfall in the monsoon core region, which could exacerbate drought conditions and agricultural stress. Conversely, during normal years, both SSP4.5-ERA5 and SSP4.5-IMD depict a shift in underestimated rainfall towards the Western Ghats, posing challenges for water availability and ecosystem resilience in these regions. Mean sea level pressure and circulation intensity analyses show that SSP4.5 consistently performs well, particularly in the Mascarene region, indicating its reliability in capturing atmospheric dynamics. However, SSP8.5 exhibits stronger rainfall in deficit years, suggesting heightened forcing impacts under this scenario. The analysis of the Somali low-level jet reveals weaker intensities in deficit and normal years under SSP8.5, despite its robustness in the Somalia region. Conversely, SSP4.5 displays favourable conditions for good rainfall in normal years, indicating its potential for capturing monsoon variability.

Comparisons with ERA5 reveal opposing trends in temperature and pressure, particularly in the Pakistan heat low, under SSP8.5 during both deficit and normal years. Additionally, the Tropical Easterly Jet appears weaker in deficit years and stronger in normal years under SSP8.5, indicating variations in monsoon strength. Overall, SSP8.5 aligns well with IMD observed data over various regions during both deficit and normal years, suggesting its utility for climate projections and impact assessments. However, the discrepancies between different scenarios and observational datasets underscore the importance of considering multiple sources of information and model uncertainties in climate research and policy-making. Further studies are warranted to validate model projections and improve the understanding of complex climate processes.

References

1. Ambaum, M. H., Hoskins, B. J., & Stephenson, D. B. (2001). Arctic oscillation or North Atlantic oscillation. *Journal of Climate*, *14*(16), 3495-3507.
2. Boos, W. R., &Kuang, Z. (2010). Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. *Nature*, *463*(7278), 218-222.
3. Clark, C. O., Cole, J. E., & Webster, P. J. (2000). Indian Ocean SST and Indian summer rainfall: Predictive relationships and their decadal variability. *Journal of Climate*, *13*(14), 2503-2519.
4. Dairaku, K., &Emori, S. (2006). Dynamic and thermodynamic influences on intensified daily rainfall during the Asian summer monsoon under doubled atmospheric CO2 conditions. *Geophysical Research Letters*, *33*(1).
5. Douville, H., Royer, J. F., Polcher, J., Cox, P., Gedney, N., DB, S., & PJ, V. (2000). Impact of CO2 Doubling on the Asian Summer Monsoon Robust Versus Model-dependent Responses. *Journal of the Meteorological Society of Japan. Ser. II*, *78*(4), 421-439.
6. Joseph, P. V., &Sijikumar, S. (2004). Intraseasonal variability of the low-level jet stream of the Asian summer monsoon. *Journal of Climate*, *17*(7), 1449-1458.
7. Knutson, T. R., & Manabe, S. (1995). Time-mean response over the tropical Pacific to increased C02 in a coupled ocean-atmosphere model. *Journal of Climate*, *8*(9), 2181-2199.
8. Koteswaram, P., & Rao, N. B. (1963). The structure of the Asian summer monsoon. *Aust. Meteor. Mag*, *42*, 35-56.
9. Krishnamurti, T. N., Bedi, H. S., & Subramaniam, M. (1989). The summer monsoon of 1987. *Journal of Climate*, *2*(4), 321-340.
10. Kumar, K. K., Kumar, K. R., & Pant, G. B. (1997). Pre–monsoon maximum and minimum temperatures over India in relation to the summer monsoon rainfall. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *17*(10), 1115-1127.
11. Patil, M. N., Patil, S. D., Waghmare, R. T., & Dharmaraj, T. (2013). Planetary Boundary Layer height over the Indian subcontinent during extreme monsoon years. *Journal of Atmospheric and Solar-Terrestrial Physics*, *92*, 94-99.
12. Qian, Y., Giorgi, F., Huang, Y., Chameides, W., & Luo, C. (2001). Regional simulation of anthropogenic sulfur over East Asia and its sensitivity to model parameters. *Tellus B: Chemical and Physical Meteorology*, *53*(2), 171-191.
13. Saitoh, E., Ueda, M., Miyajima, H., &Tatara, G. (2006). Conversion of spin current into charge current at room temperature: Inverse spin-Hall effect. *Applied physics letters*, *88*(18), 182509.
14. Sikka, D. R. (2005). From the International Indian Ocean Expedition (IIOE) to the Arabian Sea Monsoon Experiment (ARMEX)–four decades of major advances in monsoon meteorology. *Mausam*, *56*(1), 19-36.