CEEW
THE COUNCIL

Decoding India's Changing Monsoon Patterns

A Tehsil-level Assessment

Shravan Prabhu and Vishwas Chitale

Report | January 2024

Suggested citation: Prabhu, Shravan and Vishwas Chitale. 2024. *Decoding India's Changing Monsoon Patterns – A Tehsil-level Assessment*. New Delhi: Council on Energy, Environment and Water.

Cover image: iStock.

Peer reviewers: Rajeev Ahal, Director, Natural Resource Management and Agroecology, GIZ India; Dr Balaji Mani, Lead Catastrophe Model Developer, Reask; and Nandini Harihar, Programme Associate, CEEW.

Publication team: Kartikeya Jain (CEEW); Alina Sen (CEEW); The Clean Copy; Twig Designs; and FRIENDS Digital Colour Solutions.

Acknowledgment: We thank Dr Madhavan Nair Rajeevan, Distinguished Scientist and Former Secretary, Ministry of Earth Sciences, Government of India for his guidance on the study. We would like to thank Dr Mrutyunjay Mohapatra, Director General of Meteorology, India Meteorological Department and 3rd Vice President, World Meteorological Organisation for his review and valuable inputs on the study. We also thank Dr R.K. Jenamani and Dr V.K. Soni, India Meteorological Department for their review and inputs. We would like to thank Dr Thiruppugazh Venkatachalam, Dr Mohammad Rafiuddin, and Nitin Bassi for reviewing the study and providing valuable suggestions on the research methodology and climatological analysis. We would like to thank our colleague Poojil Tiwari for her inputs on the charts and figures used in this report and Neera Majumdar for helping us edit the study. We acknowledge the contribution of Aman Tiwari and Vanya Pandey in supporting the data analysis. We are grateful to Mirik Gogri, Renil Gogri and Spectrum Impact for providing funding support for this research. We thank all our colleagues at CEEW for their support, especially the outreach team for helping design, publish, and disseminate this study.

Organisation: The **Council on Energy, Environment and Water** (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. The Council uses data, integrated analysis, and strategic outreach to explain – and change – the use, reuse, and misuse of resources. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW has a footprint in over 20 Indian states and has repeatedly featured among the world's best managed and independent think tanks. Follow us on X (formerly Twitter) @CEEWIndia for the latest updates.

Council on Energy, Environment and Water
ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi – 110070, India
+91 11 4073 3300

info@ceew.in | ceew.in | @CEEWIndia | ceewindia

Decoding India's Changing Monsoon Patterns

A Tehsil-level Assessment

Shravan Prabhu and Vishwas Chitale

Report
January 2024
ceew.in

The term 'monsoon' originates from the Arabic word 'mausim', which means 'seasons', highlighting the unique characteristic of seasonal wind reversal.

Image: iStock

About CEEW

The Council on Energy, Environment and Water (CEEW) is one of Asia's leading not-for-profit policy research institutions and among the world's top climate think tanks. **The Council uses data, integrated analysis, and strategic outreach to explain — and change — the use, reuse, and misuse of resources**. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public. CEEW is a strategic/ knowledge partner to 11 ministries for India's G20 presidency.

The Council's illustrious Board comprises Mr Jamshyd Godrej (Chairperson), Dr Anil Kakodkar, Mr S. Ramadorai, Mr Montek Singh Ahluwalia, Dr Naushad Forbes, and Dr Janmejaya Sinha. The 250-strong executive team is led by Dr Arunabha Ghosh. **CEEW was certified a Great Place To Work® in 2020 and 2021**. It has also repeatedly featured among the world's best managed and independent think tanks.

In over 13 years of operations, The Council has engaged in over 450 research projects, published 380+ peer-reviewed books, policy reports and papers, created 190+ databases or improved access to data, advised governments around the world 1400+ times, promoted bilateral and multilateral initiatives on 130+ occasions, and organised 540 seminars and conferences. In July 2019, Minister Dharmendra Pradhan and Dr Fatih Birol (IEA) launched the CEEW Centre for Energy Finance. In August 2020, Powering Livelihoods — a CEEW and Villgro initiative for rural start-ups — was launched by Minister Piyush Goyal, Dr Rajiv Kumar (then NITI Aayog), and H.E. Ms Damilola Ogunbiyi (SEforAll).

The Council's major contributions include: Informing India's net-zero goals; work for the PMO on accelerated targets for renewables, power sector reforms, environmental clearances, *Swachh Bharat*; pathbreaking work for India's G20 presidency, the Paris Agreement, the HFC deal, the aviation emissions agreement, and international climate technology cooperation; the first independent evaluation of the *National Solar Mission*; India's first report on global governance, submitted to the National Security Advisor; support to the National Green Hydrogen and Green Steel Missions; the 584-page *National Water Resources Framework Study* for India's 12th Five Year Plan; irrigation reform for Bihar; the birth of the Clean Energy Access Network; the concept and strategy for the International Solar Alliance (ISA); the Common Risk Mitigation Mechanism (CRMM); India's largest multidimensional energy access survey (ACCESS); critical minerals for *Make in India*; India's climate geoengineering governance; analysing energy transition in emerging economies, including Indonesia, South Africa, Sri Lanka, and Viet Nam. CEEW published *Jobs, Growth and Sustainability: A New Social Contract for India's Recovery*, the first economic recovery report by a think tank during the COVID-19 pandemic.

The Council's current initiatives include: State-level modelling for energy and climate policies; consumer-centric smart metering transition and wholesale power market reforms; modelling carbon markets; piloting business models for solar rooftop adoption; fleet electrification and developing low-emission zones across cities; assessing green jobs potential at the state-level, circular economy of solar supply chains and wastewater; assessing carbon pricing mechanisms and India's carbon capture, usage and storage (CCUS) potential; developing a first-of-its-kind Climate Risk Atlas for India; sustainable cooling solutions; developing state-specific dairy sector roadmaps; supporting India's electric vehicle and battery ambitions; and enhancing global action for clean air via a global commission 'Our Common Air'.

The Council has a footprint in over 20 Indian states, working extensively with 15 state governments and grassroots NGOs. Some of these engagements include supporting power sector reforms in Uttar Pradesh, Rajasthan, and Haryana; energy policy in Rajasthan, Jharkhand, and Uttarakhand; driving low-carbon transitions in Bihar, Maharashtra, and Tamil Nadu; promoting sustainable livelihoods in Odisha, Bihar, and Uttar Pradesh; advancing industrial sustainability in Tamil Nadu, Uttar Pradesh, and Gujarat; evaluating community-based natural farming in Andhra Pradesh; and supporting groundwater management, e-auto adoption and examining crop residue burning in Punjab.

India receives around 76% of its total annual rainfall from the southwest monsoon during the months of June to September.

Image: iStock

डॉ. मृत्युंजय महापात्र
मौसम विज्ञाान विभाग के महानिदेशक,
विश्व मौसम विज्ञान संगठन में भारत के स्थाई प्रतिनिधि
विश्व मौसम विज्ञान संगठन के तीसरे उपाध्यक्ष

Dr. Mrutyunjay Mohapatra
Director General of Meteorology,
Permanent Representative of India to WMO
Third Vice President of WMO

भारत सरकार
पृथ्वी विज्ञान मंत्रालय
भारत मौसम विज्ञान विभाग
मौसम भवन, लोदी रोड़
नई दिल्ली–110003
Government of India
Ministry of Earth Sciences
India Meteorological Department
Mausam Bhawan, Lodi Road
New Delhi - 110003

FOREWORD

In the last few decades, climate variability and the intensity and frequency of extreme climate events have been on the rise. The latest World Meteorological Organisation (WMO) report projects that the earth surface temperature is likely to exceed the 1.5°C threshold in the next few decades. This poses a considerable risk to the growth trajectories of developing countries like India as infrastructure, population, and critical sectors such as agriculture, energy, and water resources are vulnerable to climate change impact. Here, understanding and prediction of monsoon rainfall becomes crucial as it is also being affected by climate change.

The monsoon rains, by their very nature, exhibit high variability across space and time due to a complex interplay of atmospheric and oceanic processes surrounding the Indian subcontinent. This natural variability is increasing further due to climate change, as we witness hills, cities and districts faced with flash floods, plains with riverine floods and simultaneously some areas facing the drought. To effectively navigate this rapidly evolving climate risk landscape brought by changing rainfall patterns, the understanding of monsoon variability and its latest trends at a granular level is crucial. It's equally vital to align our practices with these shifting patterns, particularly in key sectors.

India Meteorological Department (IMD) and the Ministry of Earth Sciences (MoES) are working to populate fine-resolution climate data for researchers and provide actionable forecasts of monsoon variability for decision-makers. I commend CEEW's team for their timely research endeavour, which has utilised the India Meteorological Data Assimilation and Analysis (IMDAA) reanalysis data developed as part of the National Monsoon Mission project by MoES to offer valuable insights into the evolving monsoon patterns. The findings from this research can be further used for assessing sectoral climate risks and can contribute to the development of local level climate action and disaster management plans. Relevant authorities across Indian states may utilise the information.

Climate change is a global challenge, necessitating collective action. As a critical voice for the Global South, India has shown commitment to addressing climate and disaster risk reduction. This can only be fulfilled by sharing our experiences, expertise, data, and research outcomes with the broader community.

11-01-2024

(MRUTYUNJAY MOHAPATRA)

Phone : 91-11-24611842, Fax : 91-11-24611792
E-mail : directorgeneral.imd@imd.gov.in / dgmmet@gmail.com / m.mohapatra@imd.gov.in

In 2023, all the states and UTs in India experienced extreme weather events (Ministry of Home Affairs 2023).

Image: iStock

Contents

India accounts for more than 20% of global rice production, majority of which occurs during the monsoon season (FAOSTAT 2018).

Image: iStock

Executive summary

The monsoons are crucial for the Indian economy and are often regarded as the backbone of the agricultural sector, which employs over half of India's population. They also play a pivotal role in the management of water resources and the generation of hydro-based clean energy. However, the variability of the Indian monsoons and the associated wet and dry conditions have direct impacts on socio-economic aspects of the country, including the gross domestic product (GDP) (Gadgil and Gadgil 2006; Wang, Gadgil, and Kumar 2006; Gulati, Saini, and Jain 2013).

In 2022 alone, Asia witnessed over 81 natural hazards, with 83 per cent of them being hydro-meteorological. India, in particular, incurred significant losses, primarily due to floods caused by the monsoons (WMO 2023). While the Indian monsoons, by nature, show high variability through space and time, current climate change trends indicate that we are likely to breach global warming records earlier than expected (WMO 2023). Thus, we need to answer the crucial question of how these changes are likely to affect the variability of India's most critical climatic phenomenon – the monsoons.

Existing literature predicts intensifying monsoon seasons with increased rainfall in core monsoon regions in both the medium term (up to 2050) and long term (up to 2100) under different representative concentration pathways (RCPs). Yet, capturing short-term granular spatial variabilities has been a challenge, especially beyond the district level. Existing assessments often focus on prolonged long-term trends at coarse resolutions and have not been able to account for intricate nuances within seasons, spanning across months and days, or even variations within a single district.

To fill this gap in enhanced analyses of short-term variabilities and to untangle the intricacies of the Indian monsoons, we conducted India's first sub-district -level monsoon variability assessment. Sub-districts in India are known as *tehsils, talukas, mandals, circles* and *sub-divisions*. However, we refer to them as tehsils in our study to align with the prevalent usage of the nomenclature across the majority of the country for these administrative units. We answer how rainfall patterns are changing across India during the southwest and northeast monsoon in terms of inter-annual variability (year-to-year variability) and intra-annual variability (changes within months and wet and dry extremes).

> 55% of tehsils in India witnessed an increase and 11% witnessed a decrease in southwest monsoon rainfall in the past decade (2012-2022).

For this assessment, we utilised the most recent 12-km high-resolution reanalysis data sourced from the Indian Monsoon Data Assimilation and Analysis project (IMDAA). The 12-km spatial grid covered 4419 tehsils out of 4723 tehsils as per the Survey of India shapefile obtained. Our assessment delves into trends spanning the past four decades (1982–2022), with a specific emphasis on quantifying changes in rainfall patterns in the past decade (2012–2022) during the southwest monsoon (referred to as JJAS, since it occurs from June to September) and the northeast monsoon (referred to as OND, since it occurs from October to December). We undertook a geospatial climatological analysis, employing established statistical criteria and indices endorsed by the World Meteorological Organization (WMO) and the India Meteorological Department (IMD), to accurately assess and quantify these changes.

A. Key findings

- In the past 40 years during the southwest monsoon, we found that India as a whole experienced 29 'normal', 8 'above-normal', and 3 'below-normal' monsoon years. However, analysis of these trends at the district level showed that approximately 30 per cent of India's districts witnessed a high number of deficient rainfall years and 38 per cent witnessed a high number of excessive rainfall years. Of this, **23 per cent of districts such as New Delhi, Bengaluru, Nilgiris, Jaipur, Kachchh, and Indore, witnessed both a high number of deficient as well as excessive rainfall years**.

- Decoding these trends at an even more granular level, we found that **55 per cent of tehsils witnessed an increase in southwest monsoon rainfall in the past decade (2012-2022)**, by more than 10 per cent compared to the climatic baseline (1982–2011). A statistically significant JJAS rainfall increase was observed in the traditionally drier tehsils of Rajasthan, Gujarat, central Maharashtra, and parts of Tamil Nadu.

- While the decreasing trends in southwest monsoon were not statistically significant continuously over forty years, we found that nearly **11 per cent of the Indian tehsils witnessed a decrease particularly in the past decade (2012-2022)**, by more than 10 per cent compared to the climatic baseline (1982–2011). These are in the Indo-Gangetic plains, which contribute to more than half of India's agricultural production, northeastern India, and the Indian Himalayan region. These regions also host fragile but highly diverse ecosystems. Of these tehsils, approximately **68 per cent experienced reduced rainfall in all months from June to September, while 87 per cent showed a decline during the initial monsoon months of June and July**, which are crucial for the sowing phase of kharif crops.

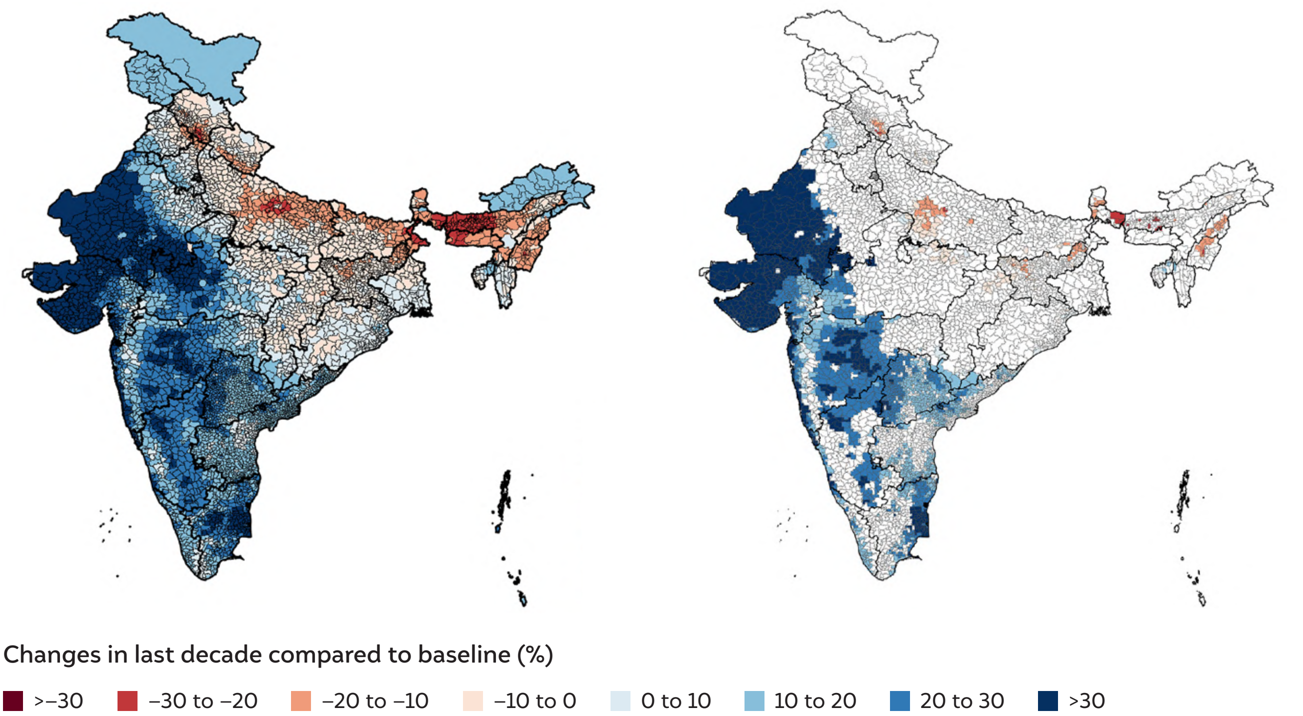
- In our study of localised wet rainfall extremes, we found that nearly **64 per cent of Indian tehsils experienced an increase in the frequency of heavy rainfall days** by 1-15 days per year in the past decade during the southwest monsoon. This pattern is prominent in the tehsils of states with the highest GDPs – **Maharashtra, Tamil Nadu, Gujarat, and Karnataka**. Furthermore, we found that in the tehsils experiencing an increase in rainfall during the southwest monsoon, the excess is coming from short-duration, heavy rainfall events.

- The rainfall associated with the northeast monsoon (OND), which primarily impacts peninsular India, has increased by more than 10 per cent in the past decade (2012-2022) in approximately **80 per cent of tehsils in Tamil Nadu, 44 per cent in Telangana, and 39 per cent in Andhra Pradesh, respectively**. While the remaining Indian states are usually dry during this period, we found a statistically significant **increasing trend in the OND rainfall along the tehsils of Maharashtra and Goa on the west coast and Odisha and West Bengal on the east coast**. This increase could partially be attributed to the cyclonic activities in the Arabian Sea and Bay of Bengal.

- Further, the analysis of monthly variability indicated that nearly **48 per cent of tehsils in India saw an increased rainfall in October** by more than 10 per cent, which could be due to the delayed withdrawal of the southwest monsoon from the subcontinent.

Image: iStock

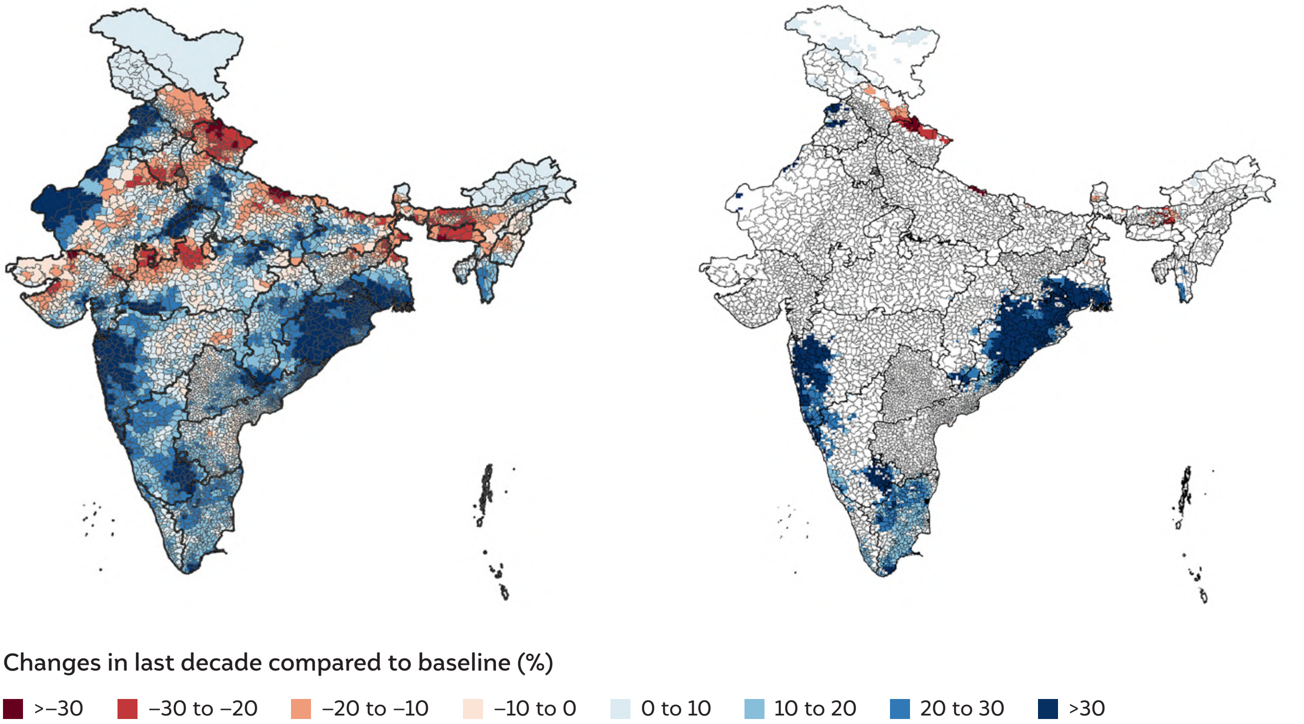
Figure ES1 The JJAS rainfall has increased in majority of the country, but decreased over Indo-Gangetic plains, north-eastern India and Indian Himalayan region in the last decade



a) Changes in JJAS rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

b) Statistically significant trends in JJAS rainfall over 40 years continuous time-series at 95% confidence level

Figure ES2 Both the western and eastern coasts of India have seen an increase in OND rainfall in last decade

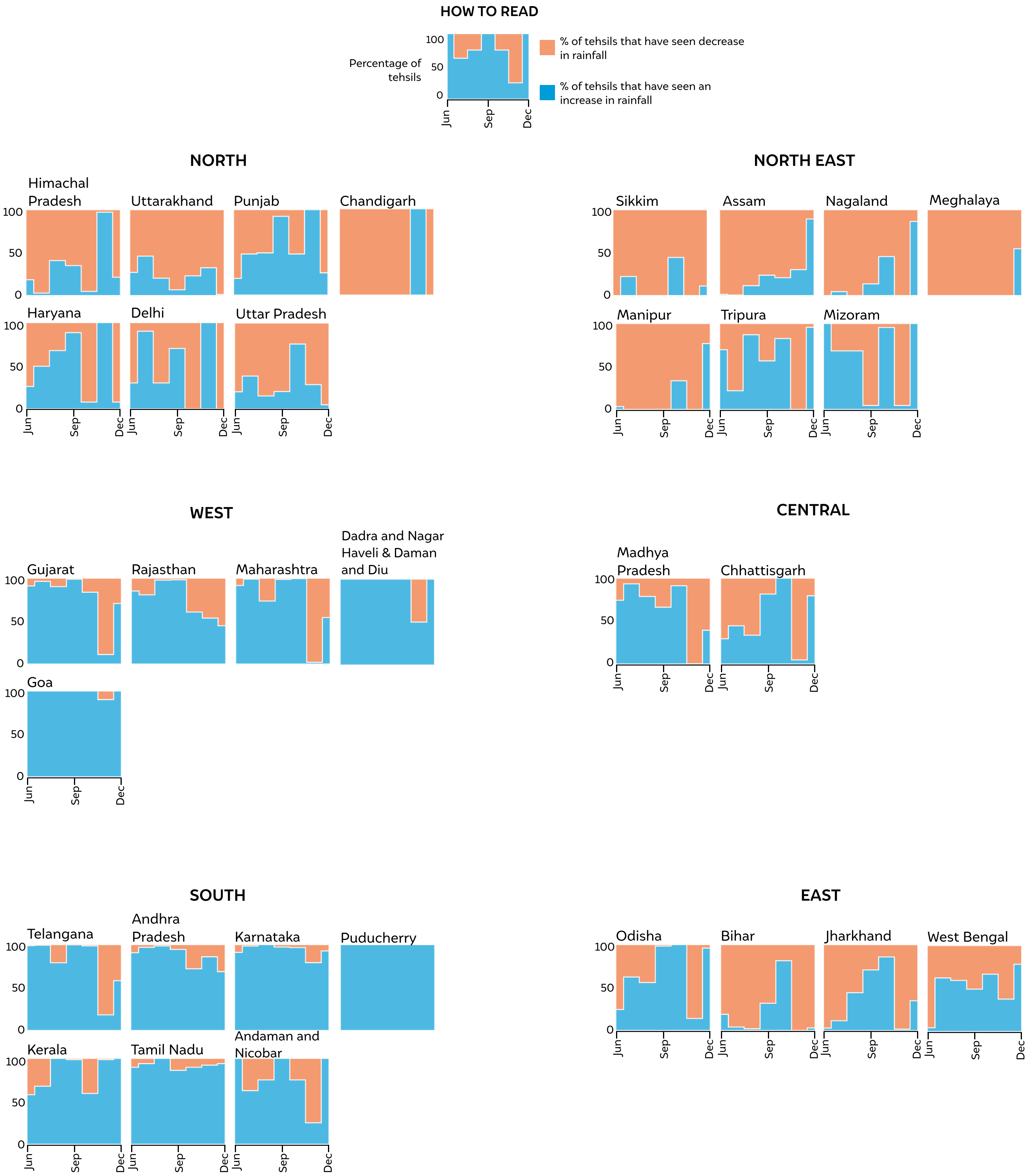


a) Changes in OND rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

b) Statistically significant trends in OND rainfall over 40 years continuous time-series at 95% confidence level

Source: Authors' analysis

Figure ES3 Majority of India's tehsils in the north and east zones show high variabilities in monthly rainfall



Source: Authors' analysis

Note: The states and UTs of Jammu and Kashmir, Ladakh, Arunachal Pradesh and Lakshadweep have not been included here due to lack of availability of tehsil-level name attributes in administrative boundary shapefile.

B. Conclusions and way forward

- **Mapping monsoon performance at more localised level based on our findings**: Considering the evolving complex trends such as high month-to-month variability and increasing occurrence of wet extremes, localised decision-making is crucial for building resilience against monsoon variability. Presently, IMD provides monsoon information at country, zonal, state, meteorological sub-division, and district scales, which is based on existing observation stations. However, this network lacks the density needed to map the monsoon at a more granular administrative level. Therefore, we utilised reanalysis data from IMDAA to map monsoon variability for all tehsils in India for both JJAS and OND seasons. We have provided the coefficient of variation (CV) and long-period average (LPA) for all tehsils considered in this study in Annexure 1, following the WMO and IMD guidelines. Local level decision-makers should use these metrics for analysing local-level monsoon performance. This will provide comprehensive, actionable insights, enhancing disaster preparedness and response.

- **Development of district-level climate action plans incorporating tehsil-level climate risk assessments**: In line with the MoEFCC's 2019 directive, all the Indian States and UTs are revising their State Action Plans on Climate Change (SAPCCs) up to 2030. While the current plans focus on district-level climate risk analysis, our findings reveal availability of tehsil-level climate information. We recommend developing district-level climate action plans, integrating this information with socio-economic and sector-specific data for detailed climate risk assessments in critical sectors like agriculture, water, and energy. The Global Goal on Adaptation requires updated climate risks assessments by 2030. However, current SAPCCs rely on prolonged climate projections upto 2050 and 2100 for adaptation strategies for the next decade. Hence, prioritising short-term projections, especially with advanced global weather prediction models at a 12-kilometre resolution as outlined in Ministry of Earth Sciences' (MoES) Atmosphere & Climate Research-Modelling Observing Systems & Services (ACROSS) scheme, is crucial. Further, to make this climate information more accessible for a diverse range of stakeholders, collaboration among research institutions, meteorological agencies, and civil society is key, drawing inspiration from global best practices like California's Cal-Adapt platform for tailored climate action plans aligning with local needs.

- **Investing in automatic weather stations and community-based recordings to capture rainfall variabilities at a hyper-local level**: Our analysis highlights diverse monsoon patterns at the tehsil level, emphasising the need for hyperlocal climate adaptation strategies. The current, most-refined long-term observational rainfall data available, at a spatial resolution of 25 km, lacks the granularity required for precise climate models and local action plans. Alternative sources such as the AWSs and citizen science can help in expanding the network of observation stations. Initiatives such as the national Weather Information Network and Data System (WINDS) and community efforts, such as school students in Kerala recording micro-weather data, offer promising avenues to enhance the assessment of micro-climatic rainfall variations and inform effective local strategies, which should be scaled up.

> Nearly 48% of tehsils in India saw increased rainfall in October in the past decade (2012-2022).


Image: iStock

1. Introduction

The southwest (June to September) and northeast (October to December) monsoons are crucial for India's economy. More than 50 per cent of the net sown area is rainfed, which accounts for approximately 40 per cent of the total production (Government of India 2023). Nearly 55 per cent of India's population is engaged in agricultural and allied sectors, and well-distributed rainfall during the kharif and rabi seasons is regarded as the backbone of the sector (Government of India 2023). Beyond its impact on agriculture, these monsoons play a pivotal role in water resource management and realising India's clean energy aspirations, particularly through the production of hydro-generated energy, which is important for it to achieve its ambitious net-zero targets.

However, monsoonal variability triggers contrasting wet and dry conditions, leading to hydro-meteorological disasters. As per an analysis of climatic disasters between 1971 and 2020 by the Council on Energy, Environment and Water (CEEW), around 75 per cent of India's districts are prone to severe hydro-meteorological disasters such as floods, droughts, and cyclones. Moreover, nearly 40 per cent of these districts show a swapping pattern, alternating between drought and floods, which leads to compounding risk. Such swapping trends can be primarily attributed to evolving rainfall patterns (Mohanty 2020). Consequently, an estimated 80 per cent of the population now resides in regions bearing the brunt of climate-induced vulnerabilities (Mohanty and Wadhawan 2021).

Current climate change trends suggest that global warming records could be breached sooner than anticipated, leading to heightened climate variability and more frequent and intense extreme weather events, which will impact an even larger population (WMO 2023). This has a direct bearing on India's monsoons, as evidenced in 2023, when unpredictable rainfall patterns triggered severe floods in some cities due to unprecedented heavy downpours, while core monsoon states faced notable rainfall deficits. For instance, Chandigarh received nearly half of its total annual rainfall in just 50 hours, while Maharashtra and Kerala encountered deficits of around 46 per cent and 60 per cent in June, respectively (IMD 2023).

> **India receives around 76% of its total annual rainfall during four months – June, July, August and September called as the southwest monsoon.**

In light of this rapidly evolving climate risk landscape, the development of effective climate adaptation policies at the sub-national level hinges on access to an exhaustive spectrum of climate information, spanning across diverse and granular spatial and temporal scales. In this issue brief, we try to decode changing patterns with respect to one of the most critical climatic variables for India – rainfall. We undertake this assessment at the tehsil level to quantify and understand trends in changes in rainfall during the southwest monsoon (between June and September) and the northeast monsoon (between October and December). We analyse the trends over the past 40 years (1982–2022), with a particular focus on the quantification of changes over the past decade, between 2012 and 2022. Our primary aim with this assessment is to offer fundamental insights into shifting rainfall patterns in recent years. These insights are intended to serve as valuable resources for policymakers and stakeholders across various sectors, including water management, agriculture, disaster preparedness, energy, and urban planning, among others, to help them make climate-informed decisions.

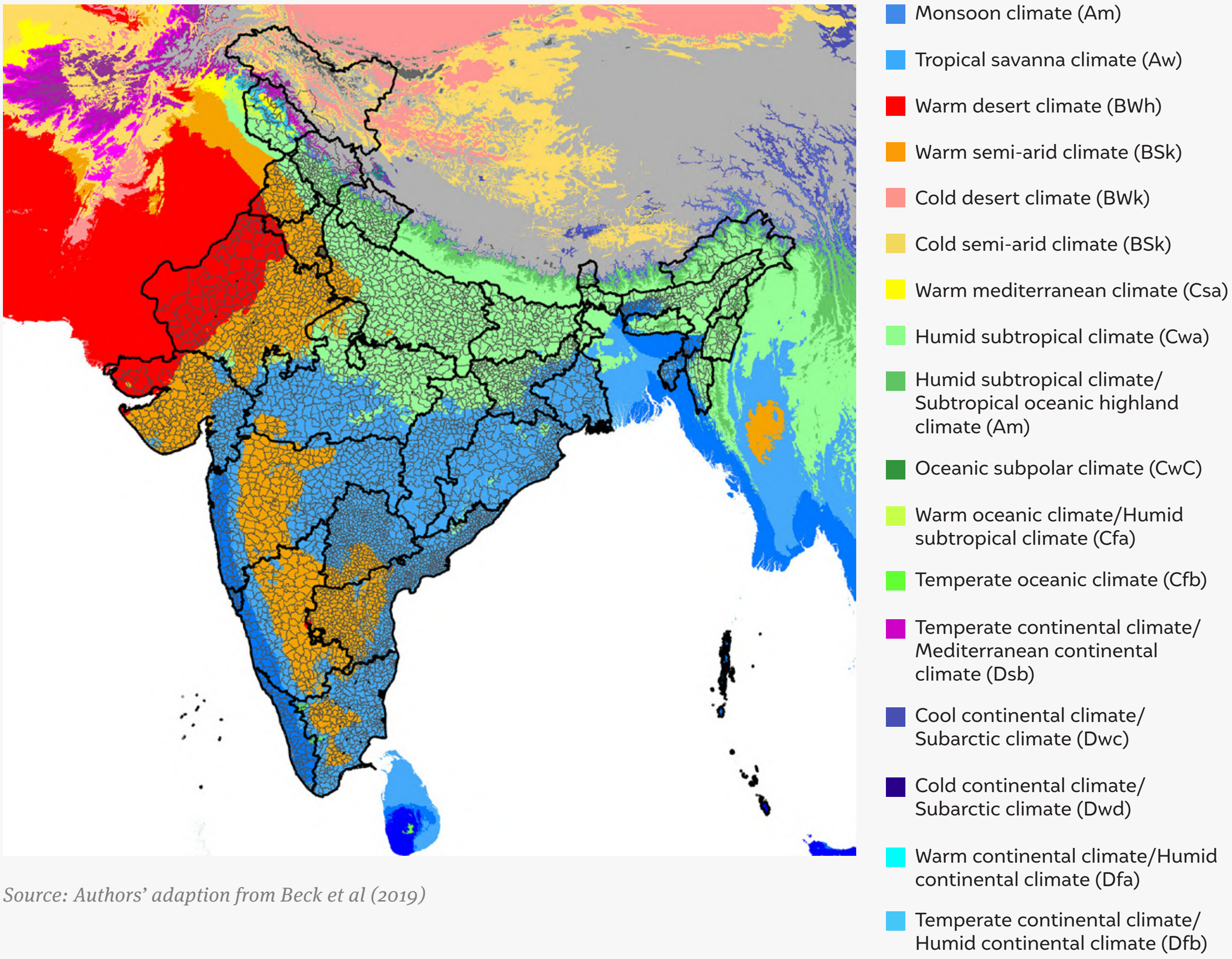

Image: iStock

BOX 1 The typology of the Indian monsoons

The term 'monsoon' originates from the Arabic word '*mausim*', which means 'seasons', highlighting the unique characteristic of seasonal wind reversal. The Indian subcontinent and its surrounding ocean, situated at the heart of this monsoonal belt, witness significant seasonal shifts in wind direction (Gadgil 2003). The Indian summer monsoon begins with a sharp rise in daily rainfall over Kerala, marking the transition from the dry season. The mean date of onset is around June 1, and by early July, the monsoon covers the entire subcontinent. Withdrawal from northwest India starts in September (Ananthakrishnan and Soman 1988; Koteswaram 1958; Wang et al. 2009). The strength of summer monsoon rainfall in India is influenced by active/break spells of increased/decreased precipitation, shaping overall monsoon patterns. These are referred to as intra-seasonal oscillations (ISOs) and are shaped by factors such as monsoon trough movements, oscillations, and synoptic systems (Shukla and Mooley 1987; Yasunari 1979; Sikka and Gadgil 1980). The primary share of India's annual rainfall occurs during the southwest/summer monsoon (June to September), except in southeast peninsular India, which experiences a rain shadow effect. During the northeast monsoon (October to December), rainfall shifts to southern India, with the prevailing northeasterly winds.

Based on this typology, in India, the climatic calendar is traditionally divided into four main seasons: (i) pre-monsoon (March to May); (ii) southwest or summer monsoon (June to September); (iii) northeast or post-monsoon (October to December); and (iv) winter (January to February). This characterisation aligns with the Köppen–Geiger classification of climatic zones.

Figure 1 **Köppen–Geiger classification of climatic zones over Indian tehsils**



Source: Authors' adaption from Beck et al (2019)

Source: Authors' compilation

1.1 Monsoon variability and climate change

The monsoons inherently exhibit substantial spatial and temporal variability (Guhathakurta et al. 2020). The significant impact of this variability across sectors has made the study of its dynamics crucial in the context of climate change and the underlying atmospheric and oceanic processes. This has led to comprehensive research efforts spanning the climate science and policy domains (Gadgil 2003; Pai et al. 2014; Rajeevan, Bhate, and Jaswal 2008; Roxy et al. 2017; Guhathakurta and Rajeevan 2008; Goswami et al. 2006; Kumar et al. 2006). In the past two decades, researchers have leveraged both observational trend analyses and machine-learning-driven atmosphere–ocean coupled general circulation models to dissect climate fluctuations and assess potential long-term adverse effects. This analytical approach has provided valuable insights into the intricate dynamics of the monsoon system and its implications.

In its report titled "Assessment of Climate Change over the Indian Region", the MoES delved into the long-term historical and projected changes in both the southwest and northeast monsoons across India (Krishnan et al. 2020). The study examined climatic trends between 1901 and 2015 and the projections under RCP4.5 and RCP8.5 till the end of the twenty-first century. Based on past climatic trends, the study reported that there was no discernible long-term trend in southwest monsoon rainfall across India as a whole. However, it highlighted pronounced spatial variability. Significant declining trends in rainfall were identified over Kerala, the Western Ghats, parts of central India, and select northeastern states. Conversely, regions such as Gujarat, the Konkan coast, Goa, Jammu and Kashmir, and the east coast experienced a significant increase in rainfall. Intriguingly, the study also found that an increase in the rate of heavy rain events offset a decrease in the rate of moderate-intensity rainfall events – that is, in regions such as central India, it was observed that the frequency of heavy rainfall events (rainfall more than 100 mm/day) increased as the frequency of moderate-intensity rainfall events decreased (rainfall between 5 and 100 mm/day). Moreover, the report underscored the fact that climate change influences not only the southwest monsoon, but also the northeast monsoon, as it was observed that the variability in northeast monsoon rainfall had escalated during the period 1959 to 2016.

> **By the end of the 21st century, India is projected to experience a 10-14% increase in southwest monsoon rainfall due to climate change.**

Analysing climate change projections using the CMIP5 multi-model ensemble, CORDEX-SA, and NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) simulations at a high-resolution 50-km grid, the assessment indicated a wetter future for the southwest monsoon in India. It predicts an increase of about 6 per cent under RCP4.5 and 8 per cent under RCP8.5 up to 2050 (near future) over India's core monsoon region, while by the end of the twenty-first century (far future), the projected increase in rainfall is expected to be approximately 10 per cent and 14 per cent as per RCP4.5 and RCP8.5, respectively. With regard to the northeast monsoon, the simulations indicated a wetter northeast monsoon in the range of 10 per cent to 50 per cent under both RCP4.5 and RCP8.5 scenarios in the near and far future across the country.

Building upon the MoES report, the IMD employed 25-km resolution grid data to assess southwest monsoon rainfall across 29 states and union territories. It concluded that during the period 1989 to 2018, while no changes were found across the majority of the country, noteworthy declines in southwest monsoon rainfall were observed in the states of the Indo-Gangetic plains and the northeastern states (IMD 2020).

In general, a comprehensive analysis of the existing literature underscores the prevailing consensus that the majority of India is poised for intensified monsoon seasons characterised by increased rainfall. However, capturing short-term and spatial variabilities at a granular scale has been a challenge. The prevailing modelled assessments predominantly concentrate on prolonged long-term trends at a coarse resolution, thereby limiting their precision in encapsulating immediate effects and within-season variations. The studies have not been able to account for intricate within-season nuances, spanning across months and days, and even the variations within a district. This gap also extends to India's current definition of a 'normal' monsoon, which is calculated as the nationwide average of total rainfall received throughout all monsoon months and does not incorporate spatial variabilities or wet and dry extremes.

Furthermore, the inherent complexities of the Indian monsoon systems introduce a further layer of uncertainty, particularly when contrasted with more predictable variables such as temperature. Studies highlight a lack of proficiency in accurately simulating the monsoons, which in turn amplifies uncertainties in comprehending future shifts (Chaturvedi et al. 2012; Saha et al. 2014; Sharmila et al. 2015; Krishnan et al. 2016). The wide inter-model spread in simulated precipitation changes over South Asia adds to the ambiguity in assessing regional hydroclimatic response (Kripalani et al. 2007; Annamalai, Hamilton, and Sperber 2007; Turner and Slingo 2009; Sabade, Kulkarni, and Kripalani 2011; Fan et al. 2010; Hasson, Lucarini, and Pascale 2013; Saha et al. 2014).

Therefore, there is an urgent need to further quantify these changes in monsoon rainfall over the recent decade at a finer spatial resolution. Consequently, in this issue brief, we embark on a comprehensive evaluation of these changes, which have been overlooked in prior assessments. This includes an examination of alterations in monthly patterns, a region-specific threshold-based assessment concerning wet extremes, and a meticulous tehsil-level analysis. Our goal is to present this information comprehensively and cohesively. To this end, we selected the following objectives for our study.

1.2 Objectives

We undertook a tehsil-level rainfall variability assessment using IMDAA's latest fine-resolution reanalysis data available at a 12-km spatial grid. This marks, to the best of our knowledge, the first tehsil-level assessment of rainfall variability in India. Our main goal is to provide fundamental insights into monsoon variability and its extremes over the past decade, between 2012 and 2022. By focusing on key monsoon seasons, we aim to assist policymakers and stakeholders from different sectors in making climate-informed decisions. We analysed inter-annual changes (year to year) and intra-annual variations (within months and extreme wet and dry anomalies) using well-established statistical criteria and indices recommended by the WMO and IMD. The main objectives of our study are as follows:

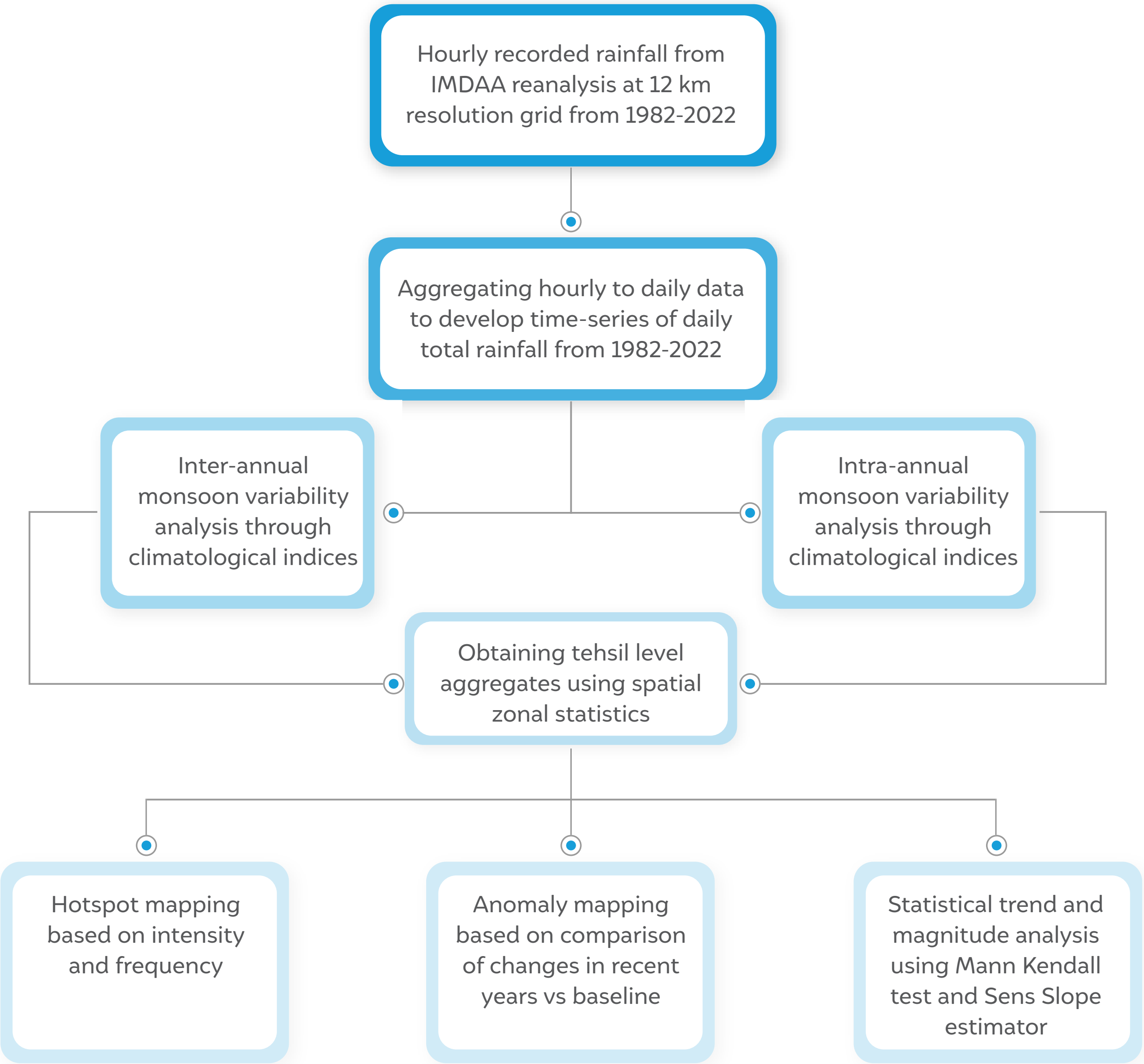
- analysing shifts in India's rainfall patterns during the southwest and northeast monsoon seasons;
- investigating changes in rainfall patterns across India at the tehsil scale during these monsoon seasons to quantify year-to-year variability and monthly anomalies; and
- identifying dry and extreme rainfall hotspots in the tehsils, including heavy rainfall events and dry days, and highlighting tehsils with high percentages of total rainfall occurring within short periods.

2. Approach and Methodology

For the exploration of climatic patterns and anomalies to be valid, adherence to the guidelines set forth by the World Meteorological Organization (WMO) is paramount. The WMO advocates for a minimum 30-year climate baseline to ensure a comprehensive assessment of anomalies and changes (WMO 2017). However, such studies need high-quality, high-resolution spatial–temporal data, given that the accuracy of the analysis hinges on data quantity and quality, and acquiring such data is challenging (Murray and Ebi 2012). Furthermore, diverse criteria are employed by different meteorological agencies and researchers globally to measure the variabilities and extremes. This underscores the need to comprehensively understand these variations. Therefore, our approach consisted of two core components: (i) compiling time-series data sheets detailing daily rainfall records across India and (ii) implementing an integrated climatological analysis to gauge inter- and intra-monsoon rainfall variability, employing a selection of indices.

> **The Indian Monsoon Data Assimilation and Analysis (IMDAA) is the finest high-resolution (~12 km) long-term climate data available for the Indian subcontinent.**

Figure 2 Schematic representation of approach and methodology



Source: Authors' compilation

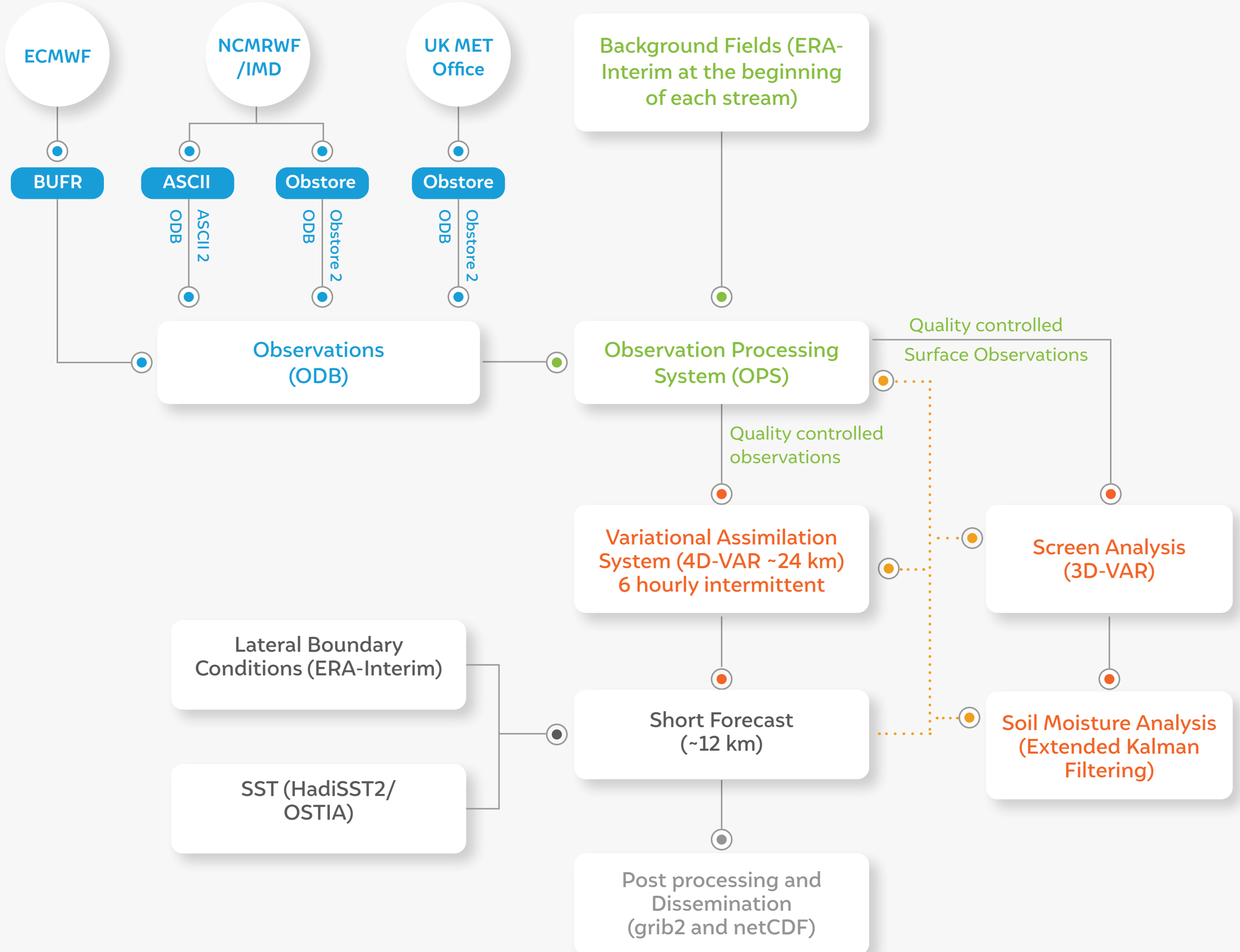
2.1 Preparation of daily time-series data sheets

For our assessment, we used the latest IMDAA reanalysis data from 1982 to 2022, which, at a 12-km grid resolution, is the finest available long-term climate data for the Indian subcontinent. This regional high-resolution atmospheric reanalysis is the first of its kind and was created through a collaboration between the National Centre for Medium-Range Weather Forecasting (NCMRWF), Met Office (UK), and IMD. The IMDAA reanalysis covers the period from 1979 to the present and uses a 4D-Var data assimilation method, making it the highest-resolution atmospheric reanalysis for India. It incorporates conventional and satellite observations, including some new ones not used in previously available reanalyses, such as the ECMWF Reanalysis version 5 (ERA5) (NCMRWF 2023).

BOX 2 Reanalysis data sets versus observation data sets: what is the difference?

Reanalysis data sets combine observations from many sources (such as ground-based stations and satellites) with numerical weather prediction models. The initial estimates come from the models, which are further adjusted by bias correction based on the observations. Observed data sets, on the other hand, are created only from recorded values at physical observation stations and are then extrapolated onto a grid.

Figure 3 **The IMDAA reanalysis system configuration**



Source: Rani et al. (2021)

Notes:
1. BUFR: Binary Universal Form for the Representation of meteorological data.
2. ASCII: American Standard Code for Information Interchange.
3. SST: Sea Surface Temperature.
4. OSTIA: Operational Sea Surface Temperature and Ice Analysis.
5. netCDF: network Common Data Form.

Source: Authors' compilation

Considering that the data is derived from reanalysis models, the need for bias correction becomes unavoidable. This correction process is already integrated into the system configuration, aligning it with IMD observation stations. Examinations of the accuracy of IMDAA data underscore its precise representation of key weather phenomena across seasons, showing good alignment with observational and reanalysis datasets such as ERA5. Notably, this reanalysis deftly captures crucial aspects of the Indian summer monsoon, including the distinctive low-level and tropical easterly jets. Moreover, the IMDAA estimates the mean, inter-annual, and intra-seasonal fluctuations of summer monsoon rainfall adequately. It even captures fine-scale features related to heavy rainfall episodes over complex terrain (Rani et al. 2021; Rani et al. 2020; Ashrit et al. 2020; Mahmood et al. 2018; Singh et al. 2021).

However, the investigations also revealed a slight inclination of the IMDAA towards registering wetter rainfall measurements during both the southwest and northeast monsoons, showing a slight difference from actual observations and ERA5 data in this aspect. It's important to acknowledge that this constraint in fully validating the complete array and spatial distribution of rainfall within the IMDAA data set stems from the scarcity of high-resolution observations across the country. Despite this limitation, the validation studies have ascertained that the IMDAA data constitutes a reliable and valuable high-resolution reanalysis data set that can be effectively used in India's weather and climate research.

2.2 Climatological analysis through indices to map inter- and intra-annual monsoon variability

To address the practical challenges posed by a changing climate variable, it is crucial to understand the behaviour of extreme values and the long-term variability of that climate variable (WMO 2017). Hence, for our tehsil-level climatological analysis, we employed a combination of indices recommended by the WMO, the IMD, and other relevant literature, as outlined in the subsequent paragraphs. These core indices provide a standardised and mutually consistent perspective on observed weather and climate changes at the global, national, and regional levels. They have been developed with the objective of informing adaptation strategies in various sectors based on their specific impacts.

Learnings from the literature suggest that while there is consistency in the indices for mapping the inter-annual variability, with well-defined criteria based on the region-specific normal, there is no consensus about the thresholds used for mapping the daily anomalies, and each study uses a different computational threshold. For example, a few studies use grid-specific thresholds, whereas some use an absolute threshold throughout the grids (Krishnamurthy, Lall, and Kwon 2009; Vidya, Anushiya, and Murthy 2022; IMD 2020; Goswami et al. 2006; Varikoden and Revadekar 2020; Vittal, Karmakar, and Ghosh 2013; Guhathakurta, Sreejith, and Menon 2011).

Table 1 **Different studies use different thresholds for mapping intra-seasonal rainfall anomalies**

Studies	Thresholds (intensity of rainfall recorded in a day)
(IMD 2020)	Rainy day: 2.5–65 mm Heavy rainfall day: >65 mm
(Goswami et al. 2006)	Moderate rainfall day: 5–100 mm Heavy rainfall day: 100–150 mm Very heavy rainfall day: >150mm
(Guhathakurta, Sreejith, and Menon 2011)	Rainy day: >2.5 mm Heavy rainfall day: 64.5–124.5 mm Very heavy rainfall day: 124.5–244.5 mm
(Vidya, Anushiya, and Murthy 2022)	Low-intensity rainfall day: <50 mm High-intensity rainfall day: 50–100 mm Very-high-intensity rainfall day: >100 mm
(Varikoden and Revadekar 2020)	Moderate rainfall day: 20–35 mm Heavy rainfall day: 35–50 mm Very heavy rainfall day: >65 mm
(Krishnamurthy, Lall, and Kwon 2009)	Heavy rainfall day: rainfall intensity at a grid >90th percentile Extremely heavy rainfall day: rainfall intensity at a grid >99th percentile
(Vittal, Karmakar, and Ghosh 2013)	Heavy rainfall day: rainfall intensity at a grid >95th percentile

Source: Authors' compilation

While employing fixed absolute thresholds (such as categorising heavy rainfall days as those with precipitation above 100 mm) has many advantages, including simplicity and ease of interpretation, opting for percentile-based thresholds provides a more uniformly distributed representation across geographical regions (Krishnamurthy, Lall, and Kwon, 2009). This technique gains heightened relevance in climate change studies with ample long-term data (WMO 2017). Given India's diverse climate, topography, and geography, we opted for percentiles to gauge extreme rainfall intensities. This approach enabled variation in the intensity threshold within tehsils, allowing us to identify localised hotspots accurately. By adopting this approach, we achieved a more precise depiction of monsoon trends and spatial patterns in India, effectively capturing the wide range of variability observed throughout the country. Furthermore, parsing trends in frequency and intensity separately proved invaluable, as the increase in frequency of events may not uniformly correlate with heightened event intensity (Trenberth 1999).

Our methodology and index selection underwent validation via stakeholder consultation involving climate and social science experts. This consultation also delved into the challenges surrounding evolving rainfall patterns and emphasised the imperative of measuring anomalies comprehensively at a granular level, beyond the administrative units of a district.

Table 2 List of indices evaluated for assessing rainfall variability

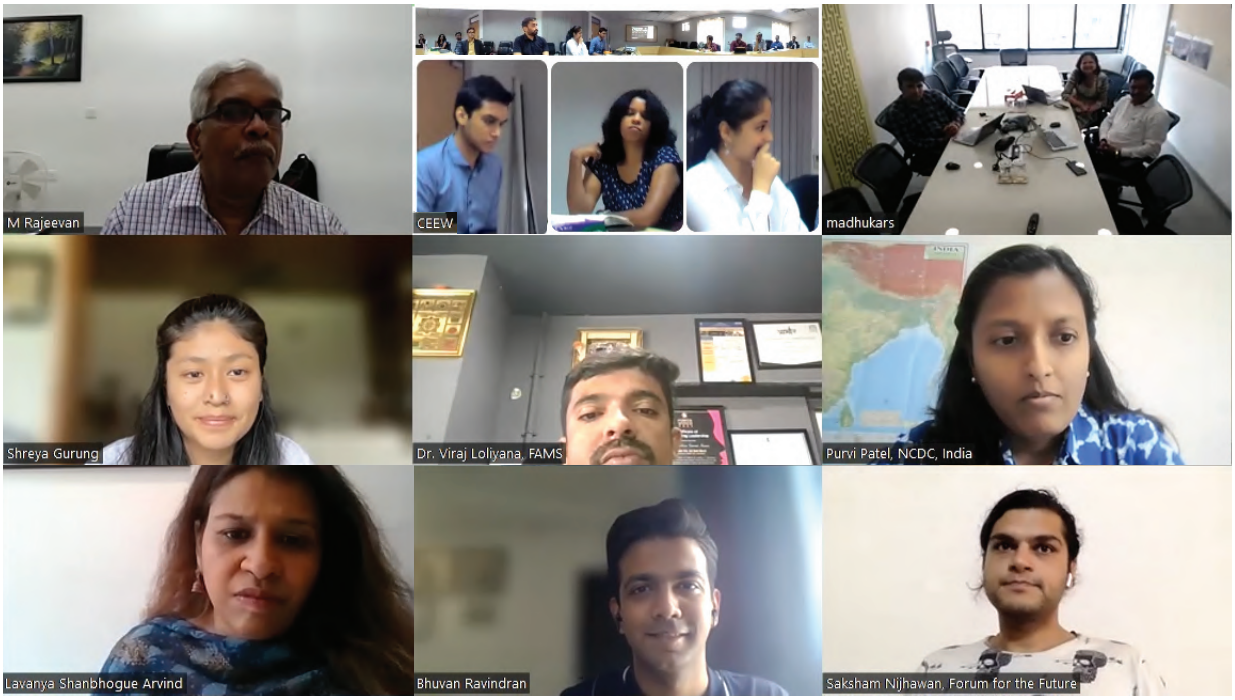
Aspect of variability	Indicator	Criteria
Inter-annual variability	Seasonal and monthly rainfall changes	Change in the total mean seasonal and monthly rainfall
	Seasonal and monthly rainfall variability	Coefficient of variation
	Number of rainfall-deficient years	Years with rainfall departure of –20% from the baseline
	Number of normal rainfall years	Years with recorded rainfall between –19% and +19% of the baseline
	Number of excess rainfall years	Years with rainfall departure of +20% from the baseline
Intra-annual variability	Frequency of dry days	Frequency of days with recorded rainfall less than 2 mm
	Frequency of moderate rainfall days	Frequency of days with recorded rainfall between 2 mm and the 90th percentile threshold
	Frequency of heavy and very heavy rainfall days	Frequency of days with recorded rainfall more than the 90th and 99th percentile threshold[1]
	Intensity of heavy and very heavy rainfall	Average intensity of rainfall when the 90th and 99th percentile thresholds were exceeded
	Percentage of seasonal rainfall received from heavy and very heavy rainfall events	Percentage of the total seasonal rainfall received on days when the 90th and 99th percentile thresholds were exceeded

Source: Authors' compilation

---

1. The percentile thresholds were computed using a five-day moving window, following the guidance of the WMO.

Figure 4 Snapshots from the CEEW consultation-cum-validation workshop



Source: CEEW

As the core objective of our assessment was quantifying recent changes or trends, we computed anomalies based on variations in the recent period (2012–2022) relative to the climatological baseline (1982–2011). The resulting spatiotemporal outputs for each indicator, in a gridded format, were subsequently aggregated to administrative units, such as tehsils, districts, and states, based on the latest shapefiles obtained from the Survey of India. It's worth noting that tehsils are known as talukas or tehsils in various regions of the country, but for consistency, we refer to them as tehsils throughout our study. The aggregation was done utilising the spatial zonal statistics[2] method. Any observed time-series trends, whether increasing or decreasing, were validated statistically using the Mann–Kendall non-parametric test[3] and Sen's slope estimator[4], maintaining a 95 per cent confidence level.

BOX 3 Limitations of and gaps in our study

It's important to highlight that our assessment primarily aimed to provide fundamental insights into changing rainfall patterns in a simplified manner, suitable for a wide range of stakeholders. As a result, we focused on employing widely accepted and easily interpretable indices that effectively capture observed variations. We did not delve into the intricacies of understanding various oceanic and atmospheric phenomena that influence the Indian monsoons, such as synoptic systems or teleconnections such as the El Niño–Southern Oscillation (ENSO) or the Indian Ocean Dipole (IOD). Additionally, the data utilised in our study is derived from reanalysis models. While bias was addressed against observational data in the model configuration, some level of bias remains inevitable. Any further correction of this bias is constrained by the lack of an extensive network of observational stations across the country.

Source: Authors' compilation

---

2. Zonal statistics enable the extraction of statistics from raster cell values within defined zones outlined by another raster or vector data set. This process involves summarising the values within specific groups of cells.
3. The Mann–Kendall test examines the sign of the trend between subsequently measured data and previously measured data. This involves comparing each later-measured value with all earlier-measured values, resulting in a total of n(n-1)/2 potential data pairs, where n represents the overall number of observations.
4. Sen's slope quantifies the extent of a trend in a data set that lacks serial autocorrelation.

3. Results and Discussion

The risks associated with climate change exhibit nonlinear characteristics, wherein the impacts can rapidly escalate despite the shifts in average conditions being gradual (King et al. 2015). Altered rainfall patterns give rise to both chronic and acute risks for ecosystems. Chronic risks emerge through gradual shifts such as reduced mean rainfall, while acute risks stem from sudden, intense events such as extreme rainfall and prolonged dry spells. These risks are interconnected, and their mitigation requires coordinated efforts across sectors and stakeholders (Pachauri et al. 2014). Notably, abrupt changes in precipitation during the Indian monsoon on decadal and centennial scales are evident from high-resolution climate proxy records spanning thousands of years (Berkelhammer et al. 2012; Sanyal and Sinha 2010).

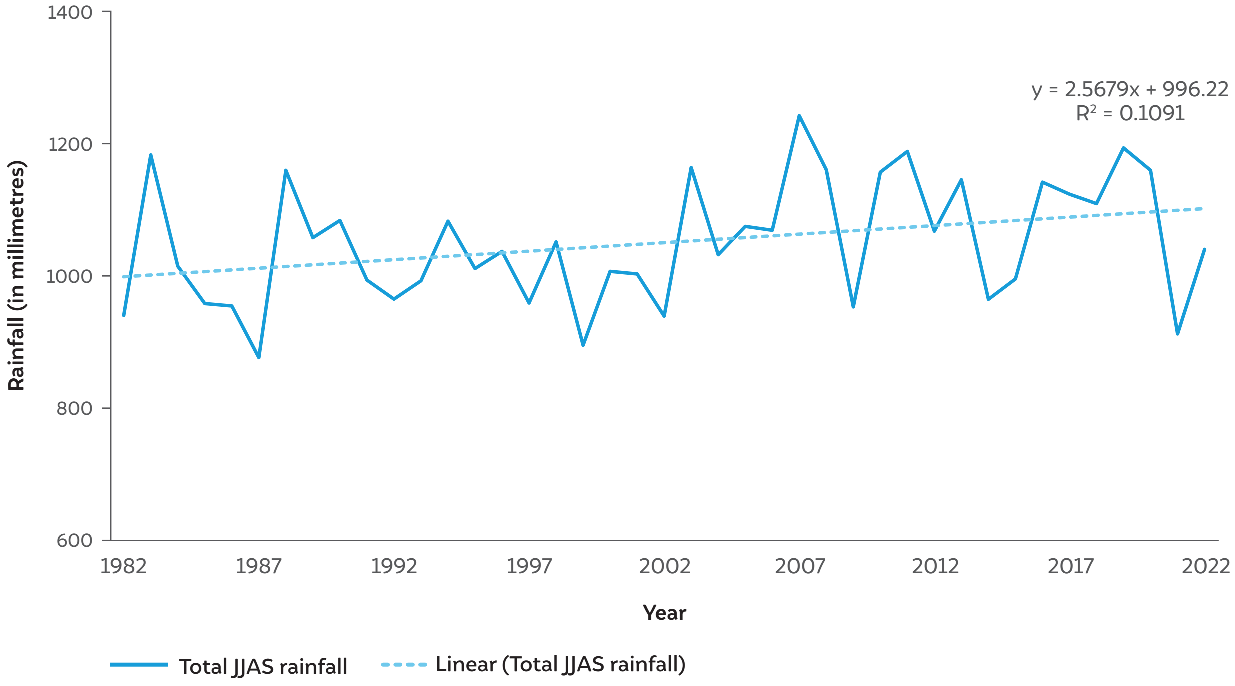
In India, there are traditionally four primary seasons (refer to Box 1). Here, we focus on two pivotal seasons for agricultural and water resource management activities – the summer or southwest monsoon season (referred to as JJAS, since it occurs between June and September) and the post-monsoon or northeast monsoon season (referred to as OND, since it occurs between October and December). By utilising indices that capture both chronic and acute risks linked to rainfall variability, our analysis aimed to provide comprehensive information on shifts in the rainfall patterns at the tehsil level in India.

3.1 Changing rainfall patterns during the southwest monsoon

As depicted in Figure 5, a trend analysis of the all-India JJAS demonstrates an overall intensification when averaged across the country, exhibiting an increasing trend at an approximate rate of 3 mm/year (as indicated by Sen's slope). Conversely, our investigation at the district and tehsil level uncovered a landscape characterised by substantial spatial variability within this trend.

To dig deeper into this pattern and uncover districts and tehsils that have shown significant year-to-year variations over the past four decades, we followed a two-step approach. First, we categorised each year based on the IMD criteria, dividing them into deficient, normal, or excessive rainfall years at the district and tehsil level. First, we categorised each year based on the IMD criteria, dividing them into deficient, normal, or excessive rainfall years at the tehsil level. At the same time, we also conducted a country-level study to determine the rainfall received by India as a whole and categorised it as normal, below-normal, or above-normal rainfall.

Figure 5 All-India averaged JJAS rainfall shows a slightly increasing trend at the rate of 3 mm/year (not statistically significant)



Source: Authors' analysis

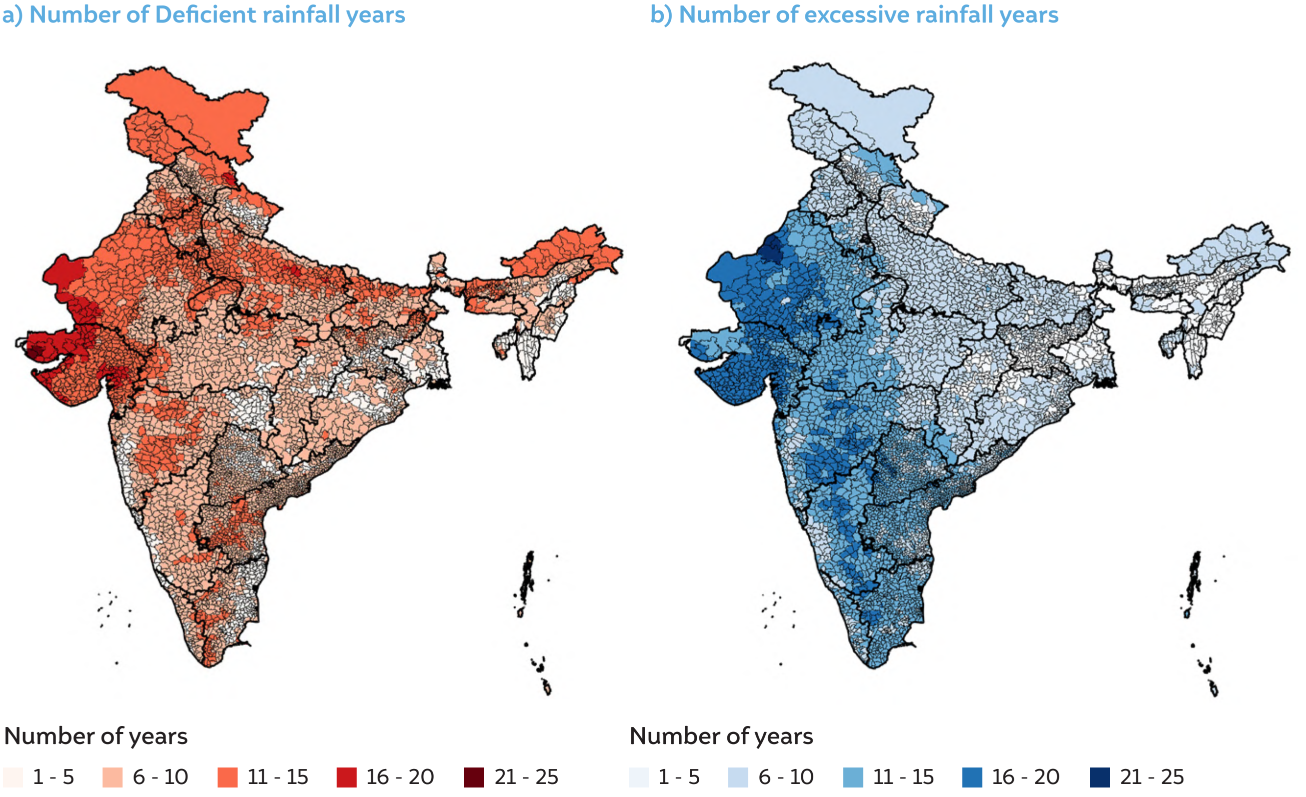
It's important to note that the IMD uses different criteria for rainfall categorisation at the regional level and the national level. For regional categorisation, we used specific thresholds outlined in Table 2. However, at the national level, rainfall is considered 'normal' when it falls within 10 per cent of its long-period average (LPA) or ranges from 90 per cent to 110 per cent of the LPA. Rainfall is deemed 'below normal' if it's less than 90 per cent of the LPA and 'above normal' if it's more than 110 per cent of the LPA (IMD 2019).

Our analysis reveals that nearly 30 and 38 per cent of India's districts witnessed a high number of deficient and excessive rainfall years (more than 10 years of 40), respectively in the past 40 years. Moreover, 23 per cent of these witnessed both a high number of deficient as well as excessive rainfall years such as New Delhi, Bengaluru, Nilgiris, Jaipur, Kachchh, and Indore. Further, at the tehsil level, nearly 24 per cent of the tehsils in India have experienced a high number of both excessive and deficient rainfall years.[5] Intriguingly, during this period, from 1982 to 2022, based on current criteria, we identified 29 years classified as 'normal' monsoon years, alongside 9 years classified as 'above-normal' and 3 years as 'below-normal' at the country level. The tehsils demonstrating such pronounced year-to-year variability are primarily concentrated in the Marathwada region of Maharashtra, along with tehsils of Rajasthan and Gujarat.

While these trends highlight a concerning pattern of erratic monsoon behaviour from one year to another, they emphasise that looking at monsoons at a coarse resolution such as a national scale doesn't adequately account for the substantial spatial variabilities observed across the country.

We analysed changes in the past decade at the tehsil level, which revealed that there is an overall increasing trend for JJAS rainfall; 55 per cent of tehsils showed an increase, while 11 per cent showed a decrease, compared to the baseline of 1982–2011 by more than 10 per cent, as seen in Figure ES1. The latter is of particular concern as a significant number of these tehsils are concentrated

Figure 6 **24% of tehsils have witnessed both a high number of deficient as well as excessive rainfall years in last four decades**



Source: Authors' analysis

---

5. We examined the distribution of excessive and deficient rainfall years across tehsils and employed GIS software to classify these tehsils accordingly. Tehsils experiencing more than 10 years (out of 40 years) of either deficient or excessive rainfall are categorised as having a high number of deficient or excessive rainfall years, respectively.

in the Indo-Gangetic plains and Himalayan states, where agricultural activities in the kharif season rely heavily on JJAS rainfall and are also highly vulnerable to hydro-meteorological disasters such as floods and droughts.

Notably, the degree of positive change surpassed that of negative change in most regions experiencing changing trends. For instance, the most substantial decrease was observed in the tehsils of Assam and Meghalaya, which have traditionally been high monsoon rainfall areas, with reductions exceeding 30 per cent (greater than 1200 mm/year compared to their LPA) in tehsils such as Pachim Nalbari Circle, Boitamari Circle, and Barnagar Circle of Assam among others. Conversely, the most notable increase was seen in the tehsils of traditionally drier areas, such as Rajasthan, Gujarat, the Konkan region, central Maharashtra, and parts of Tamil Nadu, where the increase in JJAS rainfall exceeded 30 per cent when compared to the baseline of 1981–2011.

Although the analysis of changes in JJAS rainfall as a whole offers a broad overview of variations, a closer examination on a monthly basis shows that there is significant month-to-month variation across several tehsils, as seen in Figure 7. Noteworthy among these changing patterns is the continuous decline in rainfall in tehsils situated within the Indo-Gangetic plain states, alongside substantial month-to-month fluctuations in eastern Maharashtra.

BOX 4 Increasing rainfall in the Thar desert

In the first week of August 2023, Rajasthan encountered a noteworthy increase in rainfall compared to its normal rainfall, making it the state with the highest excess rainfall across the entire country (IMD 2023). While this increase might be attributed to the intense precipitation brought by Cyclone Biparjoy, our analysis brings to light a significant transformation in the JJAS rainfall within the tehsils of Rajasthan – a state historically recognised as one of the driest regions in the Indian subcontinent. Our findings underscore the fact that nearly 77 per cent of the tehsils within the state have been witnessing an increase in JJAS rainfall over the past decade.

Recent research findings published in the journal Earth's Future reveal that the eastward movement of the Indian southwest monsoon has played a significant role in creating arid conditions in western and northwest India. Climate change–induced expansion of the warm water pool in the equatorial Indian Ocean has triggered a westward shift of the Inter-Tropical Convergence Zone (ITCZ). This study also suggests that if this trend were to continue, it could potentially transform the western and northwest regions of India into regions with a more humid 'monsoonal' climate (Rajesh and Goswami 2023).

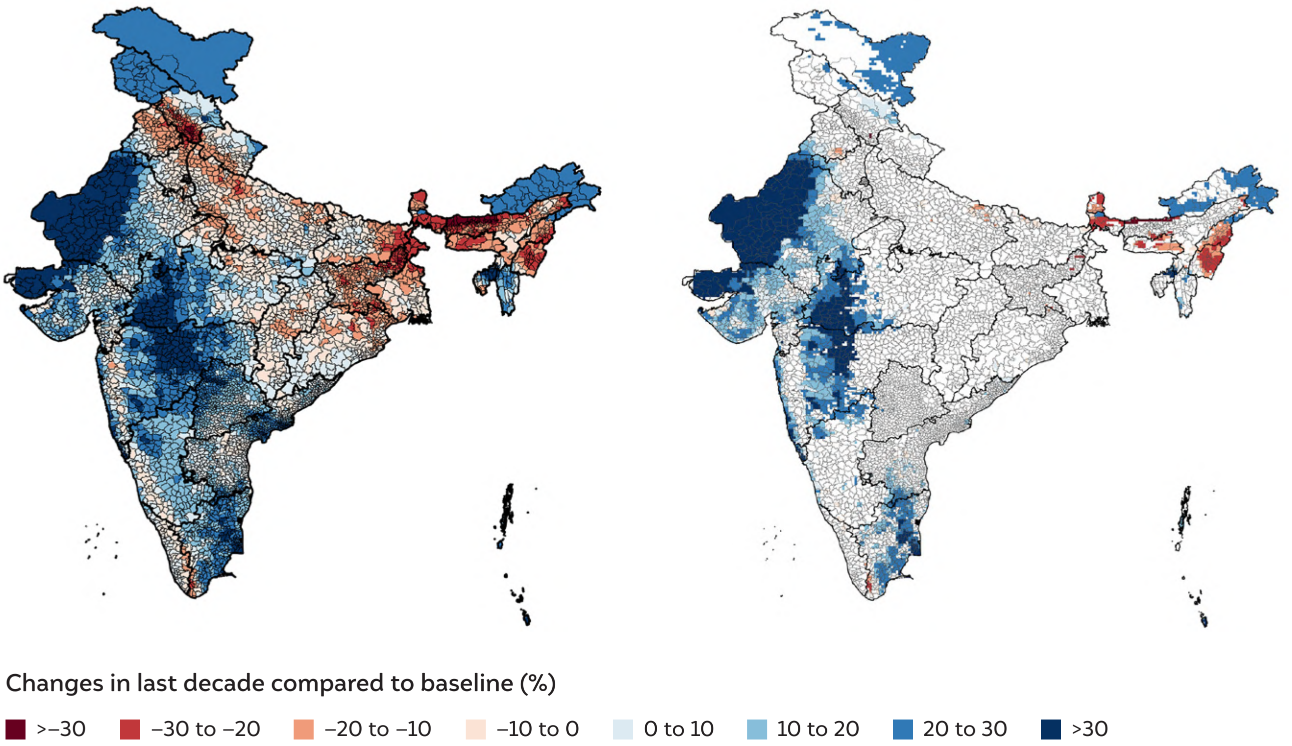
Source: Authors' compilation


Image: Alamy

Figure 7 Out of the total number of tehsils that witnessed an overall decrease in JJAS rainfall, 68% of tehsils consistently experienced reduced rainfall in all JJAS months, while 87% showed a decline during the June and July

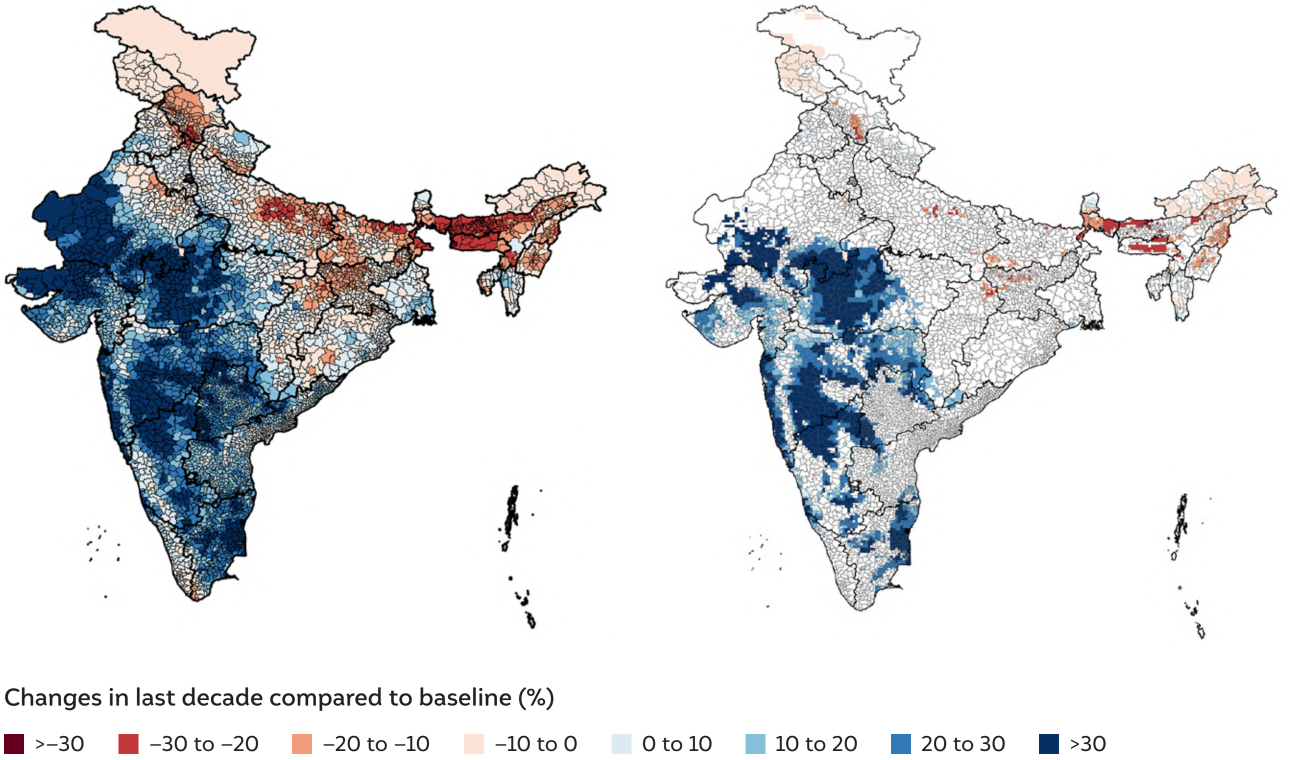
a) Changes in June rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

b) Statistically significant changes in June rainfall over 40 years continuous time-series at 95% confidence level



c) Changes in July rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

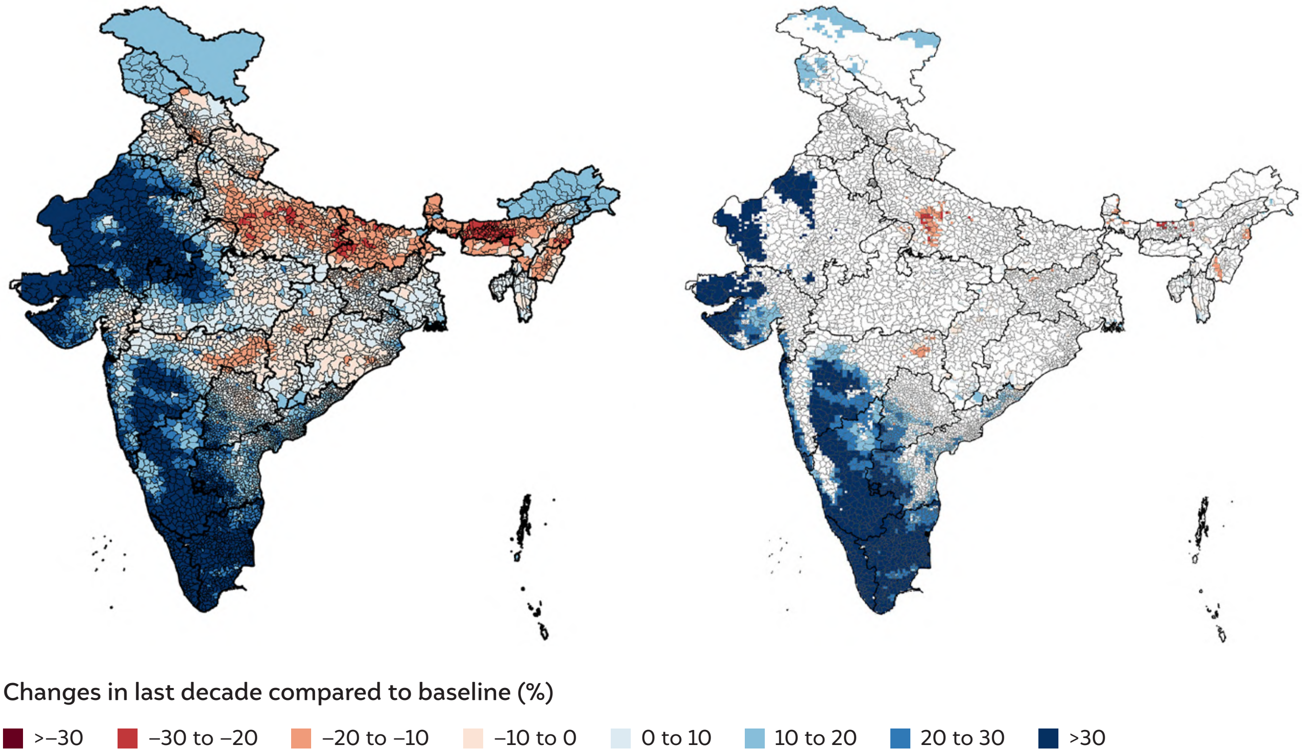
d) Statistically significant changes in July rainfall over 40 years continuous time-series at 95% confidence level



Source: Authors' analysis

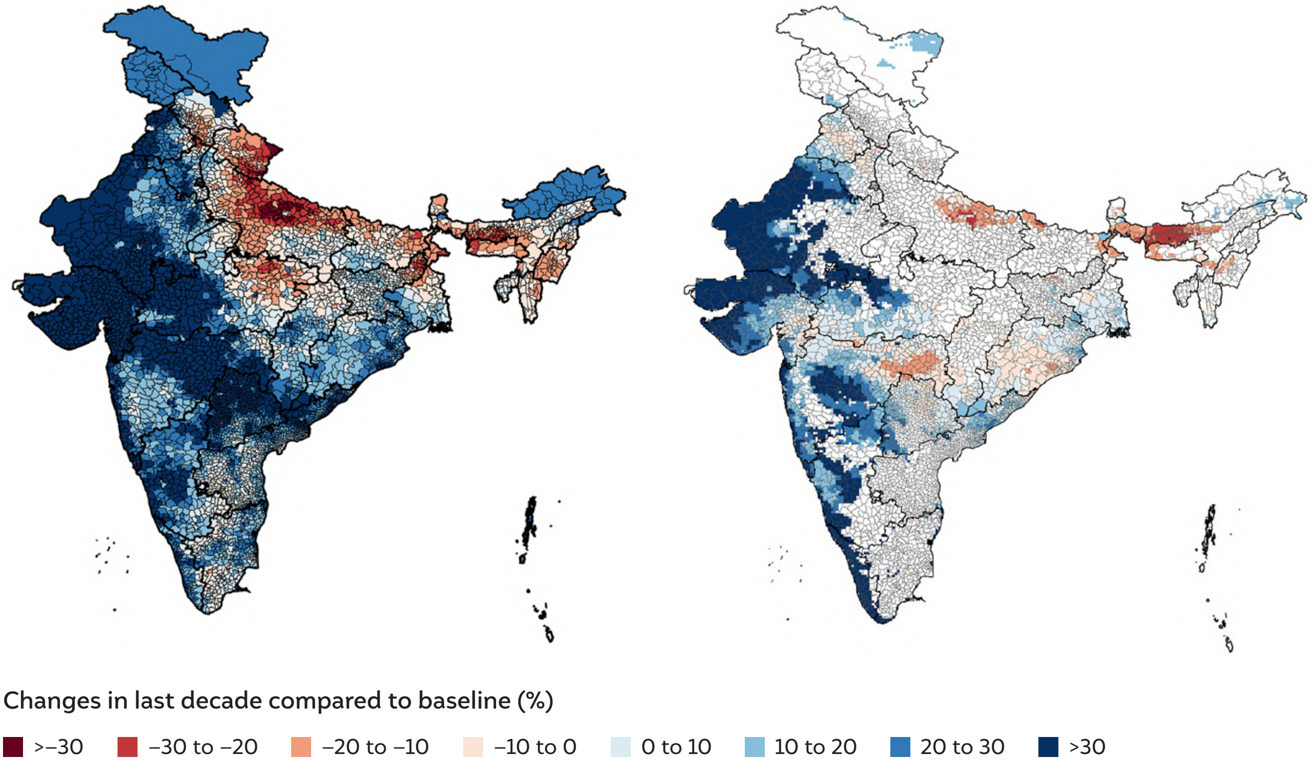
e) Changes in August rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

f) Statistically significant changes in August rainfall over 40 years continuous time-series at 95% confidence level



g) Changes in September rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

h) Statistically significant changes in September rainfall over 40 years continuous time-series at 95% confidence level



Source: Authors' analysis

Notably, the months of June and July are important for agricultural activities in India, because this is the period of sowing and establishment of crops. Our analysis showed that of the tehsils witnessing an overall decrease in JJAS rainfall, approximately 68 per cent of tehsils experienced reduced rainfall across all four months, while around 87 per cent experienced decreasing rainfall specifically in June and July, which is a critical phase of the monsoon for the timely sowing of Kharif crops. Moreover, in June, when the monsoon sets in over Kerala and advances to the western coast of India, some parts of the state witnessed a decrease in rainfall.

Our analysis revealed that nearly 55 per cent of the tehsils in the country are witnessing an increase in JJAS rainfall. However, it's crucial to assess its seasonal distribution. In our previous report on extreme hydro-meteorological disasters in India, we found a nearly three-fold increase in flood frequency nationwide, impacting nearly 34 more districts since 2005 (Mohanty 2020). Therefore, we investigated whether regions with heightened JJAS rainfall also experience more frequent and intense heavy rainfall events, using a daily variability analysis (i.e., heavy rainfall days, moderate rainfall days, and dry days). Furthermore, we evaluated the contribution of these events to seasonal rainfall.

BOX 5 Erratic monthly rainfall patterns in Vidarbha, Maharashtra

In a 2021 *Indian Express* article, Devendra Pawar, a farmers' leader in Yavatmal district of Vidarbha region of Maharashtra, highlighted that while monsoon rains arrived as scheduled, their erratic pattern posed challenges. The experience from the ground was that Vidarbha's districts often face rain deficits during the later parts of the monsoon, impacting post-sowing crop growth. As sole reliance on well water is unsustainable, Pawar stressed that sufficient rainfall distributed throughout the season was important for a prosperous harvest. Our analysis aligns with this trend, as Vidarbha and Marathwada regions exhibit highly erratic monthly anomalies. Notably, these areas experienced increased rainfall in June and July, followed by a decline in August and another increase in September. These fluctuating trends pose significant challenges to the state's agriculture and water sector (Khapre 2021).

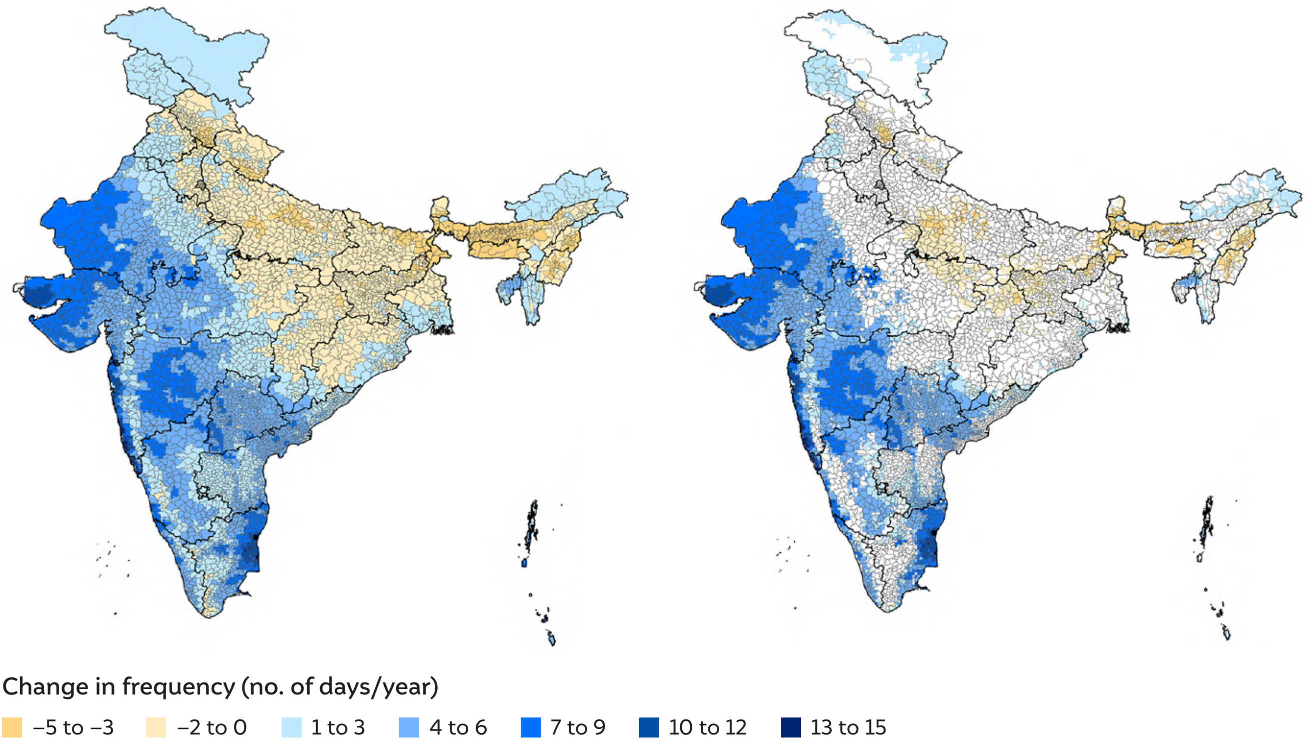
Source: Authors' compilation

Image: iStock

Figure 8 64% of Indian tehsils saw an increase in the frequency of heavy rainfall days during JJAS

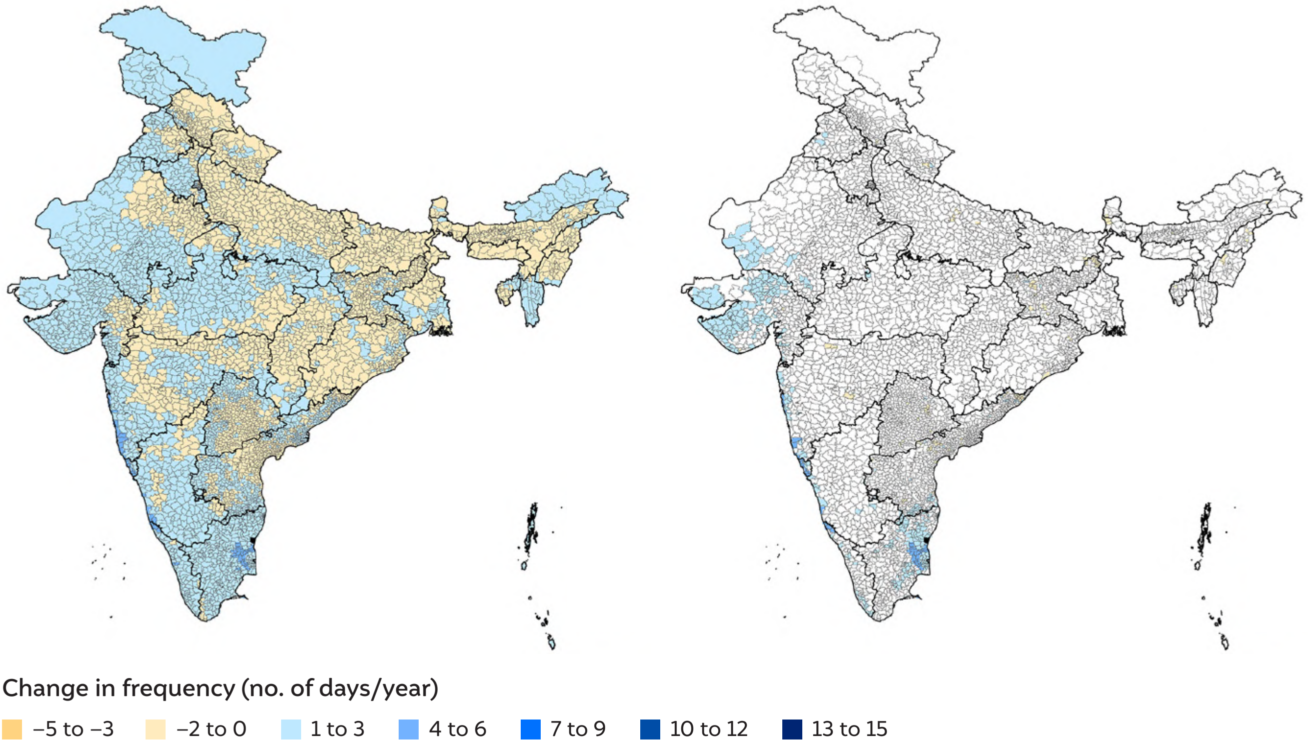
a) Changes in the frequency of heavy rainfall days in last decade (2012-2022) compared to climate baseline (1982-2011)

b) Statistically significant changes in frequency of heavy rainfall days over 40 years continuous time-series at 95% confidence level



c) Changes in the frequency of very heavy rainfall days in last decade (2012-2022) compared to climate baseline (1982-2011)

d) Statistically significant changes in frequency of very heavy rainfall days over 40 years continuous time-series at 95% confidence level



Source: Authors' analysis

We categorised wet extremes based on tehsil-specific thresholds corresponding to the 90th and 99th percentile of the baseline. For simplification purposes, we refer to them as heavy and very heavy rainfall days. We found that nearly 64 per cent of Indian tehsils experienced an increase in the frequency of heavy rainfall days by 1-15 days per year in the past decade. In addition, a few tehsils in Tamil Nadu, Gujarat and western coast of India also saw an increase in the frequency of very heavy rainfall days during JJAS by 1-5 days per year. While the majority of the country did not see any significant change in very heavy rainfall day frequency, these events, exceeding the 99th percentile threshold, typically occur rarely – about one or two days per monsoon season.

Significant increases in wet extremes have been particularly evident in the tehsils of Maharashtra, Gujarat, Rajasthan, western Madhya Pradesh, and peninsular India. Interestingly, we also noted that tehsils in the top four states with the highest gross state domestic product – namely, Maharashtra, Tamil Nadu, Gujarat, and Karnataka – experienced an increase in the frequency of heavy rainfall days (Forbes India 2023).

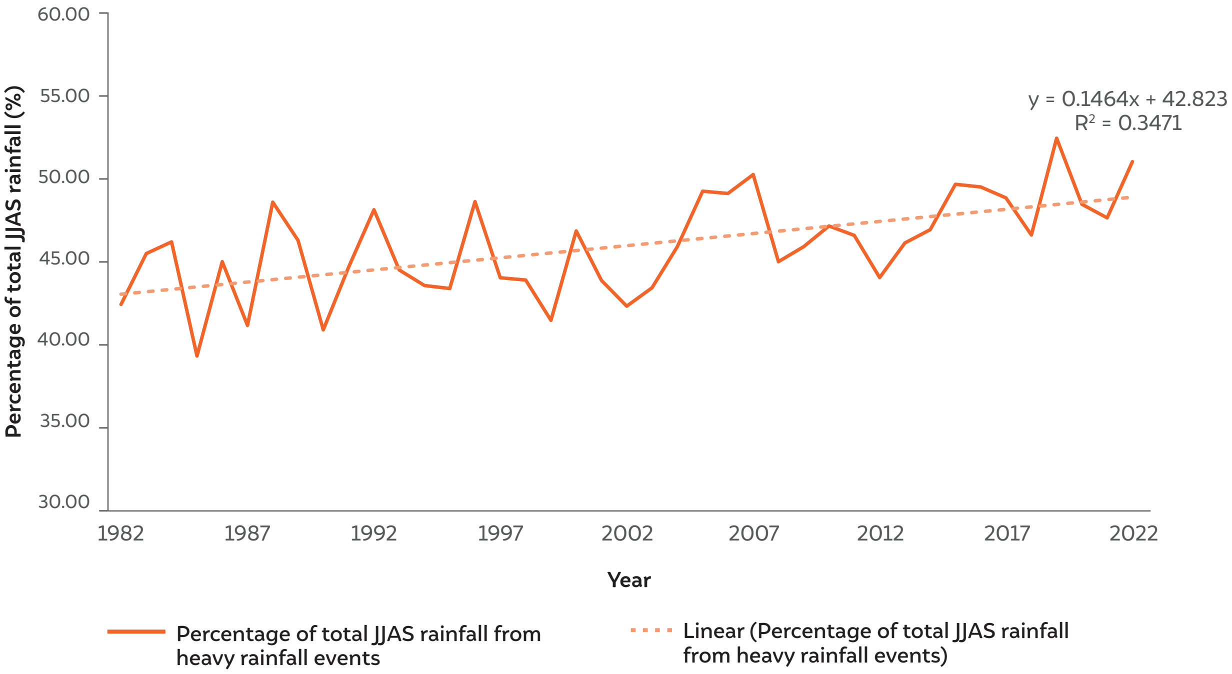
Although we observed an increase in the frequency of wet rainfall extremes, our analysis does not reveal significant trends in the intensity of these occurrences. However, a statistically significant finding does emerge – the proportion of total seasonal rainfall attributed to wet extremes is on the rise in India during JJAS. This trend is of particular concern as it is related to the distribution of rainfall within a season. This could be one of the reasons behind the recent occurrences of flash floods, such as in Delhi, Uttarakhand, Himachal Pradesh (in 2023), and Bangalore (in 2022).

BOX 6 Farmers hit hard by erratic rainfall in Bihar

A 2018 article in *The Wire* shed light on the challenges faced by smallholder farmers Mahender Rai and Ramchander Yadav in Bihar, India. Despite being unfamiliar with the term 'climate change', they have experienced its effects on their harvests. They mentioned how erratic rainfall, prolonged dry spells, and higher temperatures disrupted their agricultural cycles, leading to poor spring and autumn yields (Khan 2018). Our analysis reveals that Bihar, situated in the critical Indo-Gangetic plains, is experiencing reduced rainfall during the southwest monsoon. About 64 per cent of the state's tehsils are witnessing decreased rainfall in June and July, while 40 per cent showing reduced rainfall throughout all four monsoon months by more than 10 per cent.

Source: Authors' compilation

Figure 9 India is getting a higher proportion of its JJAS rainfall from short-lived wet extremes



Source: Authors' analysis

BOX 7 Increasing heavy rainfall events along India's west coast

Our findings suggest an increase in wet rainfall extremes along India's western coastline, encompassing the Konkan region, as well as tehsils within Gujarat. In recent times, the Arabian Sea, historically cooler in comparison to the Bay of Bengal, has seen elevated sea surface temperatures, rendering it conducive to cyclone formation. A recent study indicated a remarkable 52 per cent surge in cyclone occurrences in the Arabian Sea over the past two decades. Notably, while cyclone frequency has increased, their translation speed, or the pace of their movement, has diminished. This phenomenon has led to cyclones lasting nearly 80 per cent longer than previously (Deshpande et al. 2021). This trend of heightened cyclonic activity is believed to have amplified heavy rainfall events along the western coasts, which can be attributed to the emergence of low pressures and depressions in the Arabian Sea during June (Dave, James, and Ray 2017). Cyclone Biparjoy, which lasted for 13 days and 3 hours in mid-June 2023, was one of the longest-duration cyclones that India has witnessed in recent times.

Source: Authors' compilation

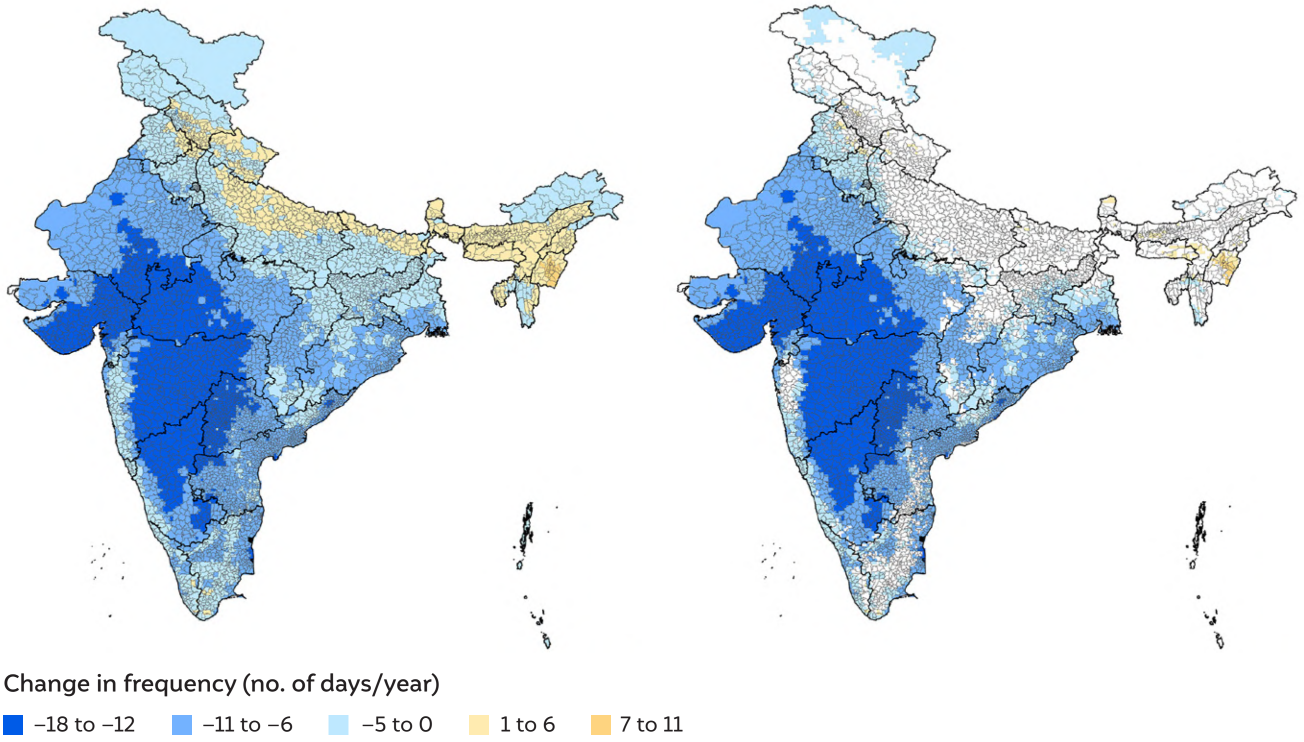
Regarding changes in the occurrence of dry days and moderate rainfall days, our analysis indicates a similar pattern to changing overall monsoon patterns. For example, the majority of the tehsils in the country which saw an increase in JJAS rainfall also saw a decrease in frequency of dry days and an increase in frequency of moderate rainfall days. However, an important observation emerges: the frequency of dry days is notably on the rise in specific tehsils along the Indo-Gangetic plains and the northeast. Interestingly, we identified contrasting trends of more dry days coupled with fewer moderate rainfall days in the affected areas. This distinct pattern is discernible in approximately nine per cent of all tehsils across India.


Image: iStock

Figure 10 Increase in the number of dry days is offset by the decrease in moderate rainfall days in 9% of tehsils during JJAS rainfall

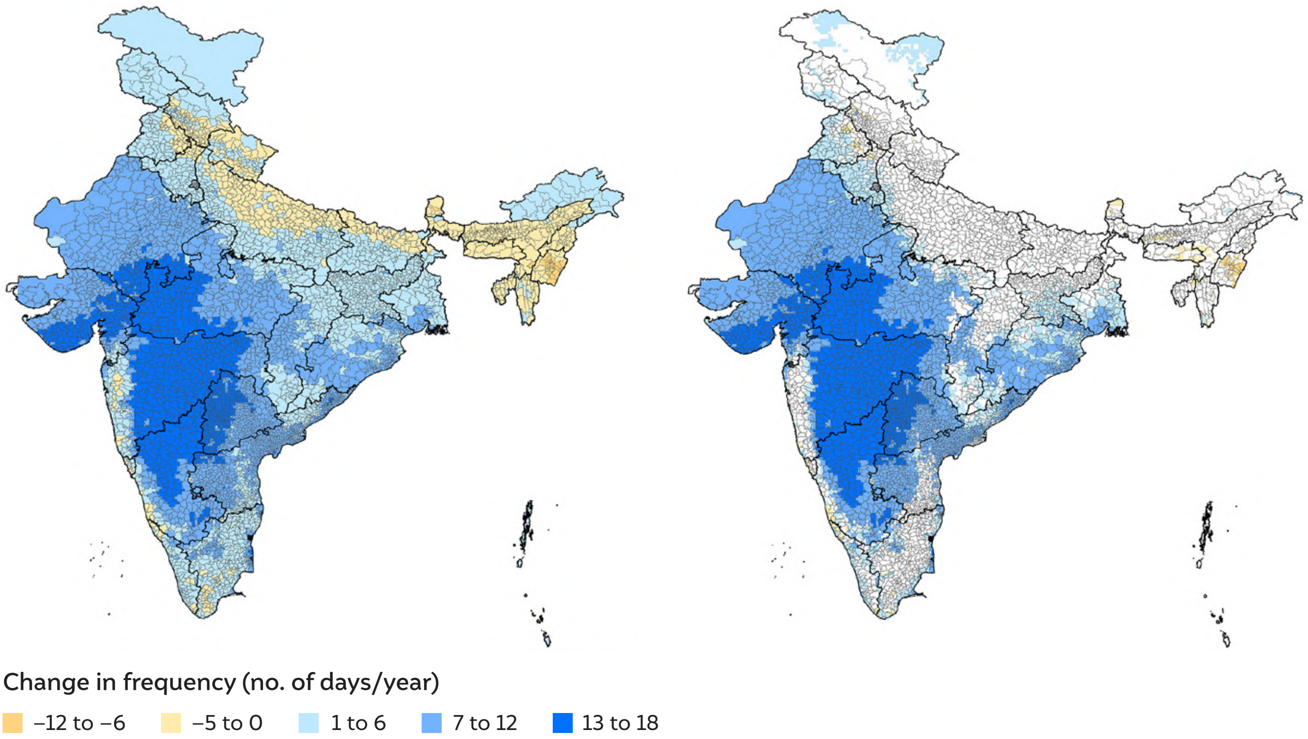
a) Changes in frequency of dry days in last decade (2012-2022) compared to climate baseline (1982-2011)

b) Statistically significant changes in frequency of dry days over 40 years continuous time-series at 95% confidence level



c) Changes in frequency of moderate rainfall days in last decade (2012-2022) compared to climate baseline (1982-2011)

d) Statistically significant changes in frequency of moderate rainfall days over 40 years continuous time-series at 95% confidence level



Source: Authors' analysis

3.2 Changing rainfall patterns during the northeast monsoon

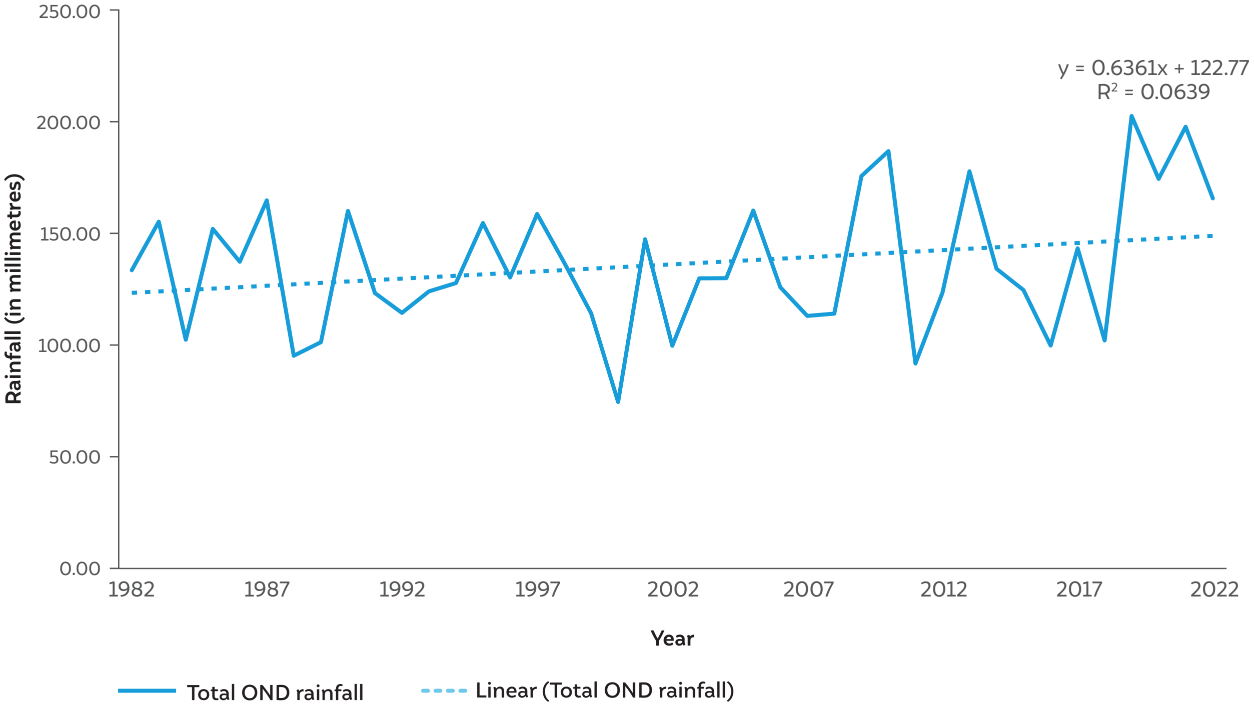
While the southwest monsoon greatly impacts India's economy, delivering the majority of its annual rainfall from June to September, the northeast monsoon from October to November holds significance for the cultivation of rabi crops across the country. This monsoon is particularly crucial for peninsular India and states such as Andhra Pradesh and Tamil Nadu, which receive up to 60 per cent of their annual rainfall during this period. The northeast monsoon significantly affects the cultivation of rice and maize in Tamil Nadu and Andhra Pradesh (Krishna Kumar et al. 2004). The rainfall during the northeast monsoon exhibits high variability both spatially and temporally. The coefficient of variation (inter-annual) for the northeast monsoon rainfall averaged over five subdivisions is 25 per cent, exceeding that of the southwest monsoon rainfall averaged over the entire country (10 per cent). The peninsula in the south is renowned for its substantial year-to-year variability (Rajeevan et al. 2022).

As seen in Figure 11, we observe a similar phenomenon with the northeast monsoon as we did with the southwest monsoon. Over the past four decades, there has been a slight increasing trend in the rainfall during the northeast monsoon across the country. This trend reflects a gradual increase at a rate of 0.7 mm/day, according to Sen's slope estimator, though it's worth noting that this trend is not significant.

Over the past decade, there have been significant changes in the northeast monsoon patterns across the regions it impacts. As depicted in Figure ES1, regarding alterations in OND rainfall within the core states it affects, our analysis revealed that the OND rainfall increased in nearly 80 per cent of Tamil Nadu's tehsils, 44 per cent of Telangana's tehsils, and 39 per cent of Andhra Pradesh's tehsils in the past decade compared to the climate baseline by more than 10 per cent.

Furthermore, even though the northeast monsoon mainly affects peninsular India and the OND rainfall contribution constitutes only a small portion of the annual rainfall in the Indian mainland, we observed changing patterns in these tehsils as well. For example, the tehsils showing an increase in OND rainfall in the past decade compared to the climate baseline are in Odisha, south West Bengal, and the Konkan region. Conversely, a decrease is observed in tehsils of Uttarakhand, Himachal Pradesh, Haryana, and northeastern states such as Meghalaya and Assam.

Figure 11 **The northeast monsoon over India shows a slightly increasing trend, at the rate of 0.7 mm/year (not statistically significant)**



Source: Authors' analysis

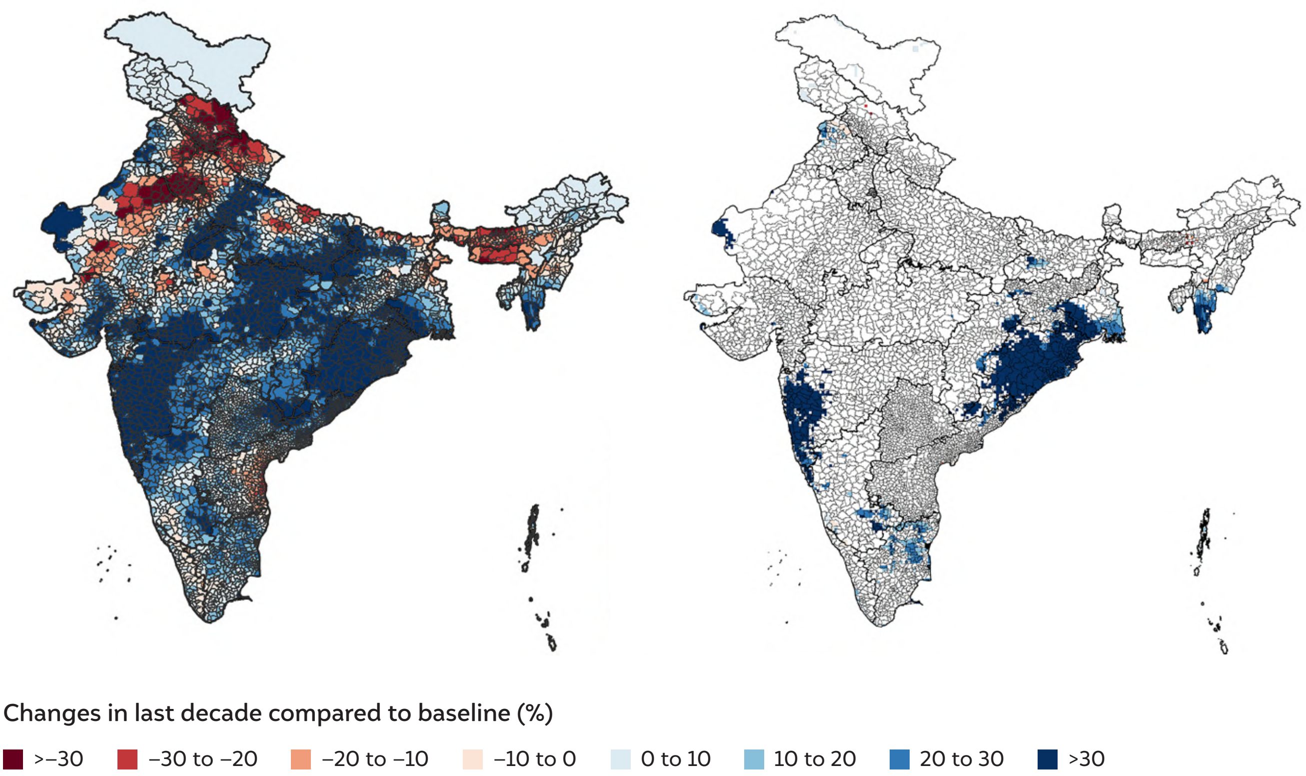
The OND season, also known as the retreating monsoon season or post-monsoon season, witnesses a shift in the rainfall zone to the southern regions of India, Sri Lanka, and the adjacent sea. As the southwest monsoon recedes from the northern parts of India, the mean sea level pressure and upper tropospheric wind circulation patterns undergo a swift transition from the summer monsoon type to the winter type. By October, the ITCZ or monsoon convergence zone, previously situated over northern India, starts shifting southwards (Rajeevan et al. 2022).

BOX 8 Decreasing OND rainfall and forest fires

Our analysis highlights a decline in OND rainfall in the states of Uttarakhand and Himachal Pradesh as well as in northwestern Madhya Pradesh and certain parts of Vidarbha in Maharashtra. Approximately 86 per cent of tehsils in Uttarakhand are experiencing a reduction in the northeast monsoon. While OND rainfall typically contributes a relatively small portion of the annual precipitation in these regions, it is intriguing to note that these states' forests also align with areas classified as Extremely Fire-Prone Forests according to the Forest Survey of India (FSI 2022). The forest fire season spans from November to March in India. However, the vegetation starts drying out once the JJAS season is over. While many forest fires are human-induced, untimely high temperatures and deficient rainfall during the winter can exacerbate vegetation dryness, creating conditions conducive to the rapid spreading of fires. The decreasing OND rainfall in these fire-prone regions heightens concerns that the frequency and intensity of forest fires as well as the area affected by them could increase.

Source: Authors' compilation

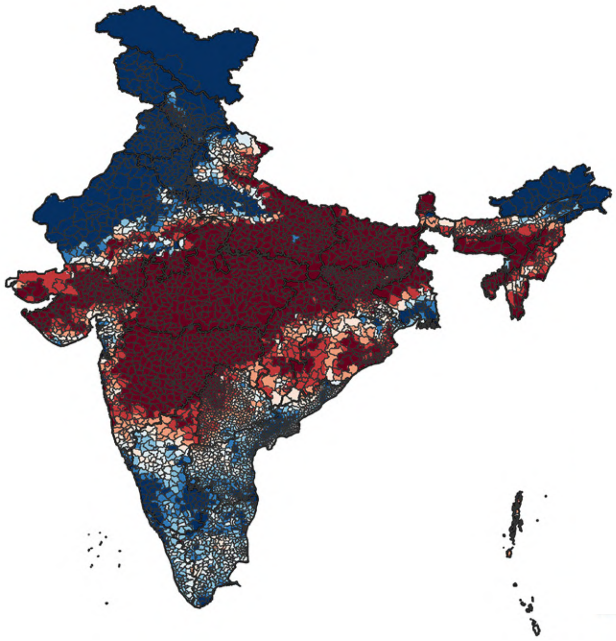
Figure 12 48% of tehsils in India saw an increase in October rainfall in the past decade



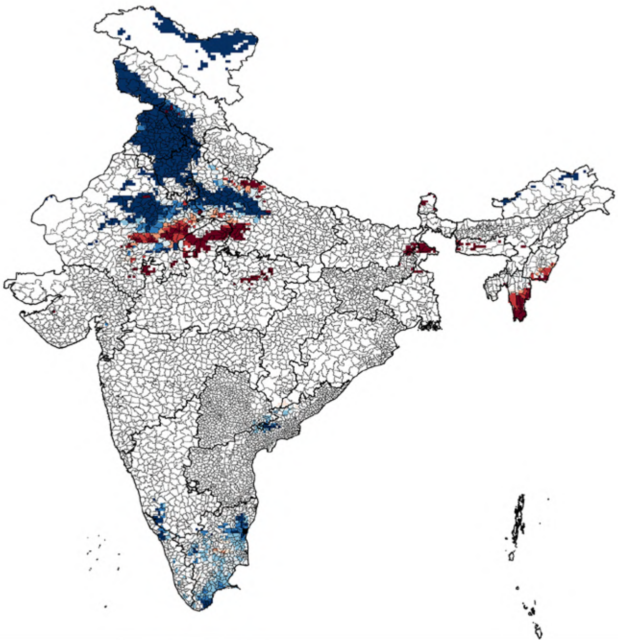
a) Changes in October rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)

b) Statistically significant changes in October rainfall over 40 years continuous time-series at 95% confidence level

c) Changes in November rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)



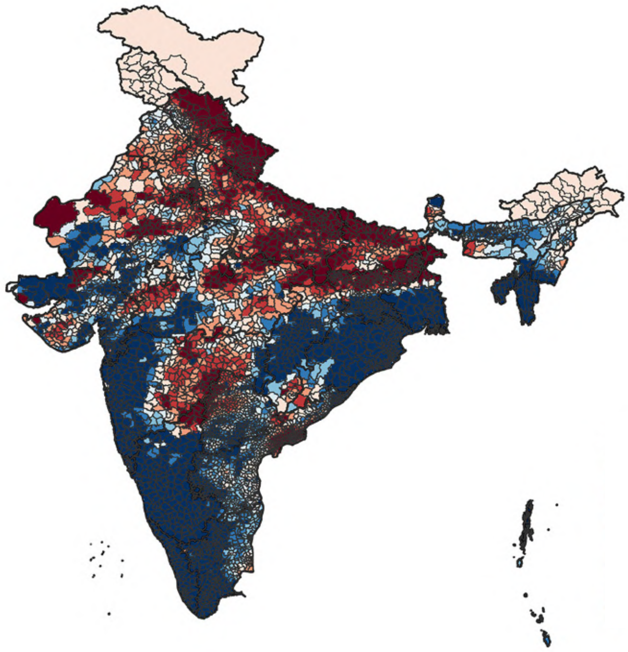
d) Statistically significant changes in November rainfall over 40 years continuous time-series at 95% confidence level



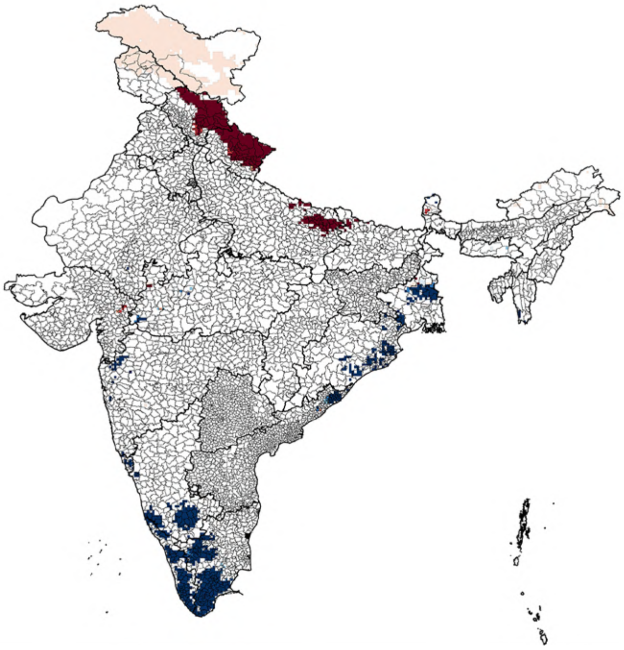
Changes in last decade compared to baseline (%)

■ >–30 ■ –30 to –20 ■ –20 to –10 ■ –10 to 0 ■ 0 to 10 ■ 10 to 20 ■ 20 to 30 ■ >30

e) Changes in December rainfall in last decade (2012-2022) compared to climatic baseline (1982-2011)



f) Statistically significant changes in December rainfall over 40 years continuous time-series at 95% confidence level



Changes in last decade compared to baseline (%)

■ >–30 ■ –30 to –20 ■ –20 to –10 ■ –10 to 0 ■ 0 to 10 ■ 10 to 20 ■ 20 to 30 ■ >30

Source: Authors' analysis

Our analysis of monthly OND rainfall changes reveals a remarkably variable trend characterised by significant month-to-month variations. Notably, our findings indicate that around 48 per cent of the tehsils have been witnessing an increase in October rainfall during the past decade by more than 10 per cent, which could be due to the delayed withdrawal of the southwest monsoon over the mainland, as evident in 2023 (IMD 2023).

While examining wet and dry rainfall extremes, we observed minor shifts occurring in India's coastlines, as the frequency of heavy rainfall days was found to be increasing in the range of 1-5 days per day in the past decade. However, the majority of the country experiences a lower intensity of heavy rainfall events during this period compared to the southwest monsoon period and hence, the extent of the increase is relatively modest in comparison and could be attributed to the post monsoon cyclonic activity in the region. Our analysis revealed no notable or substantial changes in the frequency and intensity of very heavy rainfall events, dry days, or moderate rainfall days.

4. Conclusions and way forward

The impacts of climate change are becoming increasingly evident worldwide. According to a recent report by the WMO, Asia is the world's most disaster-prone region (WMO 2023). In 2022 alone, Asia experienced over 80 hydro-climatic disasters, which directly affected approximately 50 million people. Notably, floods and droughts accounted for nearly 70 per cent of the total economic losses resulting from hydro-climatic disasters in Asia during that year. In the context of India, the loss and damages were primarily associated with floods during the monsoon season. The total economic loss from these disasters was estimated to be USD 4.2 billion (WMO 2023).

The Indian monsoons are intricately influenced by atmospheric and oceanic processes, naturally displaying significant variability in both space and time. However, our analysis, along with the findings from the reviewed literature, indicates a worrisome intensification of this variability, which can be largely attributed to climate change.

Given these circumstances, it has become crucial to study the intricacies of rainfall variability in order to gain new insights into the performance of both the southwest and northeast monsoons in India. Consequently, there is an urgent need not only to access detailed climate information that reflects the latest trends, but also to accurately capture localised variabilities through tailored thresholds. This is particularly relevant for countries such as India, which has one of the most diverse climate profiles globally.

Therefore, to build resilience against changing monsoon patterns, there is a pressing need for localised decision-making. This involves analysing monsoon performance accurately, re-evaluating strategies in key sectors, and formulating adaptation action plans tailored to the specific needs of each locality.

BOX 9 Changes in the onset and withdrawal dates of the southwest monsoon

Traditionally, the onset and withdrawal dates for the southwest monsoon over the Indian mainland were fixed as June 1 and September 30, respectively. However, in 2020, IMD revised these dates. The previous dates were based on records from a limited number of stations (149 stations) during the period 1901–1940. The updated normal onset dates were determined using data from 1961 to 2019, while withdrawal dates were revised based on data from 1971 to 2019 (IMD 2020).

The date of onset of the monsoon over Kerala remained June 1 consistently. However, the new monsoon advance dates for states such as Maharashtra, Gujarat, Madhya Pradesh, Chhattisgarh, Telangana, Andhra Pradesh, Odisha, Jharkhand, and Bihar were delayed by three to seven days compared to the old 'normal' dates. Regarding monsoon withdrawal, significant changes were made to the dates for central and northwest India, with delays of almost 7–14 days compared to the former dates. Interestingly, there was no change in the final withdrawal date over South India, which remained October 15. This shift in onset and withdrawal dates aligns with our findings of decreased rainfall in many tehsils in June and increased rainfall in October across the Indian mainland.

Source: Authors' compilation

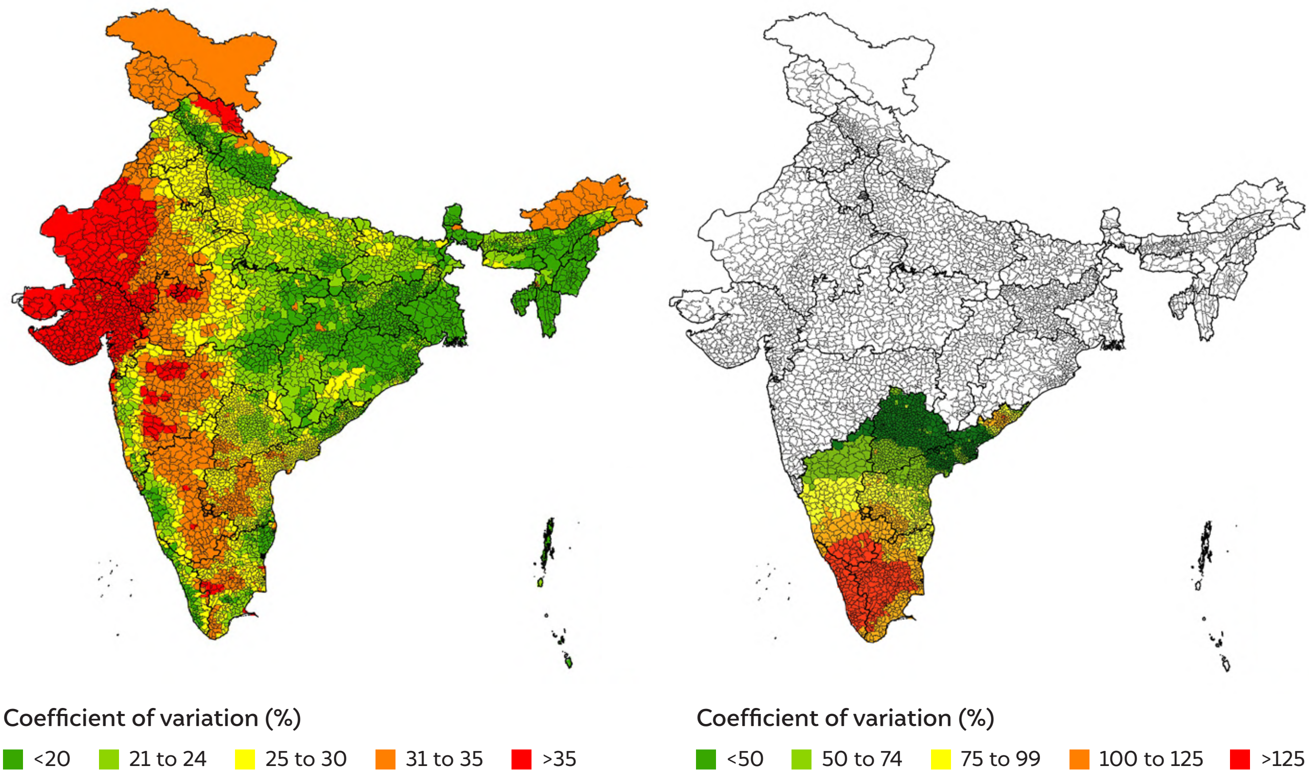
4.1 Mapping monsoon performance at more localised level based on our findings

We found significant spatial variabilities in changing rainfall patterns as well as high month-to-month variability, with increasing occurrence of extreme rainfall events. Considering these evolving complex trends, localised decision-making is crucial for building resilience against increasing monsoon variability.

Presently, IMD provides monsoon information at country, zonal, state, meteorological sub-division, and district scales, based on existing observation stations. However, this network lacks the density needed to map the monsoon at a more granular administrative level. Therefore, we utilised reanalysis data from IMDAA to map monsoon variability for all tehsils in India for both JJAS and OND seasons. Annexure 1 includes the coefficient of variation (CV) and long-period average (LPA) for all tehsils considered in this study, following WMO and IMD guidelines outlined in Chapter 2. Figure 13 a and b depict the CVs for JJAS and OND rainfall, while Annexure 1 contains CVs for both seasons and individual months. These metrics can assist local decision-makers in analysing monsoon performance for upcoming years.

While the total quantum of rainfall is crucial for mapping performance across the considered temporal scale, it is equally important to adopt new frameworks that consider monthly variability and contrasts between dry and wet extremes at a finely detailed spatial scale when assessing monsoon performance. Studies like Mishra, Tiwari, and Kumar (2022) have proposed such frameworks, which can offer more actionable insights into monsoon performance, contributing to enhanced disaster preparedness and response.

Figure 13 Tehsil-wise coefficient of variation



a) Southwest monsoon (JJAS)

b) Northeast monsoon (OND)

Source: Authors' analysis

Note: OND CV figure represents tehsils of only states the northeast monsoon primarily impacts. However, Annexure 1 contains the CV for all tehsils in India.

4.2 Development of district-level climate action plans incorporating tehsil-level climate risk assessments

Based on the directive framework from the MoEFCC in 2019, most states are currently in the process of submitting their revised SAPCCs up to 2030. While the initial focus of climate risk analysis in these plans is at the district level, as evident in our findings, tehsil level climate information is available due to data-democratisation initiatives such as the National Monsoon Mission.

We recommend that all districts in India should develop district-level climate action plans where this information needs to be synergised with detailed socio-economic and sector-specific data to craft meticulous climate risk assessments, particularly for pivotal sectors such as energy, water, and agriculture, which bear the brunt of climate impacts.

As per the latest Global Goal on Adaptation, each country is required to conduct updated assessments of climate hazards, impacts, and exposure to risks and vulnerabilities by 2030. However, existing SAPCCs heavily rely on prolonged trends upto 2050 and 2100 derived from CORDEX-based RCMs and statistically downscaled CMIP models. These methods face challenges in capturing nuanced variations within the intricate Indian monsoon system, particularly over smaller spatial scales and shorter time frames.

For effective planning towards 2030, there is a pressing need for more short-term projections. Thus, prioritising the development of advanced global weather prediction models at a 12-kilometre horizontal resolution, as outlined in the MoES' ACROSS scheme, becomes crucial. Additionally, fostering collaboration between research institutions, meteorological agencies, and civil society organisations is essential to make climate information more accessible for a diverse range of stakeholders. Drawing insights from global best practices, such as California's Cal-Adapt platform, which is recognised for supporting local hazard mitigation and aiding climate policy, can be instrumental. Implementing such strategies can facilitate the creation of tailored and granular climate action plans that align with local needs.

4.3 Investing in automatic weather stations and community-based recordings to capture rainfall variabilities at a hyper-local level

Our evaluation of monsoon variability at the tehsil level underscores the significant diversity in monsoon rainfall patterns on a local scale. It becomes increasingly clear that hyper-local climate adaptation strategies are needed to cope with these variations. Consequently, there is a demand for hyper-local data that encompasses both climate-related and socio-economic variables to inform these strategies effectively. Currently, the most refined observational rainfall data available operates at a 25-km spatial resolution and is derived from 6955 rain gauge station records countrywide (Pai et al. 2014). However, a significant increase in this number is needed if more precise climate models and hyperlocal action plans are to be developed. In this context, data democratisation through the augmentation of alternative weather recording sources, such as AWS, gains prominence. A positive step in this direction is WINDS, an integral component of the Pradhan Mantri Fasal Bima Yojana, which provides AWS-recorded real-time weather information. Similarly, noteworthy instances of community engagement, such as school students in Kerala recording 24-hour rain data, humidity, wind speed, and direction to comprehend micro-weather patterns and climate, present an avenue for amplifying such efforts to enhance the assessment of micro-climatic rainfall variabilities (Philip 2023).

Acronyms

ACROSS	*Atmospheric, Climate Science and Services Scheme*
AWS	automatic weather station
CEEW	Council on Energy, Environment and Water
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRIDA	Central Research Institute for Dryland Agriculture
ECMWF	European Centre for Medium-Range Weather Forecasts
MoEFCC	Ministry of Environment, Forest, and Climate Change
ENSO	El Niño–Southern Oscillation
ERA	European Environment Agency
FSI	Forest Survey of India
ICAR	Indian Council of Agricultural Research
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
IMDAA	Indian Monsoon Data Assimilation and Analysis project
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
ISO	intra-seasonal oscillations
ITCZ	inter-tropical convergence zone
JJAS	June, July, August, September
LPA	long-period average
MoES	Ministry of Earth Sciences
NCMRWF	National Centre for Medium Range Weather Forecasting
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Projections
OND	October, November, December
RCM	regional climate model
RCP	representative concentration pathways
SAPCC	state action plan on climate change
UK	United Kingdom
USD	United States Dollar
WINDS	Weather Information Network and Data System
WMO	World Meteorological Organization
WRF	Weather Research & Forecasting Model

References

Ananthakrishnan, R., and M. K. Soman. 1988. "The Onset of the Southwest Monsoon over Kerala: 1901–1980." *Journal of Climatology* 8 (3): 283–96.

Annamalai, H., K. Hamilton, and K. R. Sperber. 2007. "The South Asian Summer Monsoon and Its Relationship with ENSO in the IPCC AR4 Simulations." *Journal of Climatology* 20 (6):1071–92. https://doi.org/10.1175/JCLI4035.1.

Ashrit, Raghavendra, S. Indira Rani, Sushant Kumar, S. Karunasagar, T. Arulalan, Timmy Francis, Ashish Routray, et al. 2020. "IMDAA Regional Reanalysis: Performance Evaluation during Indian Summer Monsoon Season." *JGR Atmospheres* 125 (2). https://doi.org/10.1029/2019JD030973.

Berkelhammer, Max, A. Sinha, Lowell Stott, H. Cheng, Francesco S. R. Pausata, and K. Yoshimura. 2012. "An Abrupt Shift in the Indian Monsoon 4000 Years Ago." *Climates, Landscapes, and Civilizations* 198:75–88.

Beck, Hylke E., Niklaus E. Zimmermann, Tim R. McVicar, Noemi Vergopolan, Alexis Berg, and Eric F. Wood. "Present and future Köppen-Geiger climate classification maps at 1-km resolution." Scientific data 5, no. 1 (2018): 1-12.

Chaturvedi, R. K., J. Joshi, M. Jayaraman, G. Bala, N. H. Ravindranath. 2012. "Multi-Model Climate Change Projections for India under Representative Concentration Pathways." *Current Science* 103 (7): 791–802.

Vidya, Anushiya, and Murthy 2022. "Climate Atlas of India: District-Level Analysis of Historical and Projected Climate Change Scenarios." Center for Study of Science, Technology and Policy. https://cstep.in/publications-details.php?id=2282.

Dave, Hiren, M. E. James, and Kamaljit Ray. 2017. "Trends in Intense Rainfall Events over Gujarat State (India) in the Warming Environment Using Gridded and Conventional Data." *International Journal of Applied Environmental Sciences* 12 (5): 977–98.

Deshpande, Medha, Vineet Kumar Singh, Mano Kranthi Ganadhi, M. K. Roxy, R. Emmanuel, and Umesh Kumar. 2021. "Changing Status of Tropical Cyclones over the North Indian Ocean." *Climate Dynamics* 57:3545–67.

Fan, Fangxing, Michael E. Mann, Sukyoung Lee, and Jenni L. Evans. 2010. "Observed and Modeled Changes in the South Asian Monsoon over the Historical Period." *Journal of Climate* 23:5193–205. https://doi.org/10.1175/2010JCLI3374.1.

Forbes India. 2023. "GDP of Indian States & Union Territories." Last modified September 22, 2023. https://www.forbesindia.com/article/explainers/gdp-of-indian-states-union-territories/88157/1.

FSI. 2022. *India State of Forest Report 2021*. Dehradun: Forest Survey of India. https://fsi.nic.in/forest-report-2021-details.

Gadgil, Sulochana. 2003. "The Indian Monsoon and Its Variability." *Annual Review of Earth and Planetary Sciences* 31 (1): 429–67.

Gadgil, Sulochana, and Siddhartha Gadgil. "The Indian Monsoon, GDP and Agriculture." 2006. *Economic and Political Weekly* 41 (47): 4887–95.

Goswami, Bhupendra Nath, Vengatesan Venugopal, Debasis Sengupta, M. S. Madhusoodanan, and Prince K. Xavier. 2006. "Increasing Trend of Extreme Rain Events over India in a Warming Environment." *Science* 314 (5804): 1442–45.

Government of India. 2023. "Economic Survey: Development Imperative of Rural India" [Press release]. Last modified January 29, 2023. https://pib.gov.in/PressReleasePage.aspx?PRID=1894901.

Guhathakurta, Pulak, B. L. Sudeep Kumar, Preetha Menon, Ashwini Kumar Prasad, S. T. Sable, and S. C. Advani. 2020. *Observed Rainfall Variability and Changes over Kerala State*. Pune: India Meteorological Department.

Guhathakurta, Pulak, and Madhavan Rajeevan. 2008. "Trends in the Rainfall Pattern over India." *International Journal of Climatology: A Journal of the Royal Meteorological Society* 28 (11): 1453–69.

Guhathakurta, Pulak, O. P. Sreejith, and Preetha A. Menon. 2011. "Impact of Climate Change on Extreme Rainfall Events and Flood Risk in India." *Journal of Earth System Science* 120:359–73.

Gulati, Ashok; Shweta Saini and Surbhi Jain. 2013. Monsoon 2013: Estimating the impact on agriculture, Working Paper, No. 269, Indian Council for Research on International Economic Relations (ICRIER), New Delhi.

Hasson, S., V. Lucarini, and S. Pascale. 2013. "Hydrological Cycle over South and Southeast Asian River Basins as Simulated by PCMDI/CMIP3 Experiments." *Earth System Dynamics* 4:199–217. https://doi.org/10.5194/esd-4-199-2013.

IMD. 2020. "Observed Monsoon Rainfall Variability and Changes" [Press release]. India Meteorological Department, March 30. https://reliefweb.int/report/india/india-meteorological-department-observed-monsoon-rainfall-variability-and-changes.

IMD. 2023. *All India Weather Summary and Forecast Bulletin*. New Delhi: India Meteorological Department.

IMD. n.d.a "Monsoon FAQ." India Meteorological Department. Accessed November 12, 2022. https://mausam.imd.gov.in/imd_latest/monsoonfaq.pdf.

IMD. n.d.b "New Normal Dates of Onset/Progress and Withdrawal of Southwest Monsoon over India." India Meteorological Department. Accessed October 9, 2023. https://mausam.imd.gov.in/Forecast/marquee_data/IMD%20Press%20release_New%20onset%20and%20withdrawal%20dates%28Final%29.pdf.

Indira Rani, S., John P. George, T. Arulalan, Sumit Kumar, M. Das Gupta, E. N. Rajagopal, and Richard Renshaw. 2020. "Evaluation of High Resolution IMDAA Regional Reanalysis Precipitation over India during Summer Monsoon Season." In *CLIVAR Exchanges, No. 79, – Special Issue: India's Monsoon Mission*, edited by Madhavan Nair Rajeevan and Jose Santos, 31–33. World Climate Research Programme. https://doi.org/10.36071/clivar.79.2020.

Indira Rani, S., T. Arulalan, John P. George, E. N. Rajagopal, Richard Renshaw, Adam Maycock, Dale Barker, and M. Rajeevan. 2021. "IMDAA: High Resolution Satellite-Era Reanalysis for the Indian Monsoon Region." *Journal of Climate* 34 (12): 5109–33. https://doi.org/10.1175/JCLI-D-20-0412.1.

Khan, Mohd Imran. 2018. "Climate Change Hits Bihar Farmers Twice This Year." *The Wire*, October 27, 2018. https://thewire.in/agriculture/climate-change-hits-bihar-farmers-twice-this-year.

Khapre, Shubhangi. 2021. "Farmers in Maharashtra's Rain-Deficit Vidarbha Region Worry Over Kharif Crops." *The Indian Express*, August 22, 2021. https://indianexpress.com/article/cities/mumbai/farmers-in-maharashtras-rain-deficit-vidarbha-region-worry-over-kharif-crops-7465763/.

King, David, Daniel Schrag, Zhou Dadi, Qi Ye, and Arunabha Ghosh. 2015. *Climate Change: A Risk Assessment*. London: UK Foreign & Commonwealth Office.

Koteswaram, P. 1958. "The Easterly Jet Stream in the Tropics." *Tellus* 10 (1): 43–57.

Kripalani R., J. H. Oh, A. Kulkarni, S. S. Sabade, and H. S. Chaudhari. 2007. "South Asian Summer Monsoon Precipitation Variability: Coupled Climate Model Simulations and Projections under IPCC AR4. *Theoretical and Applied Climatology* 90 (3–4): 133–159.

Krishna Kumar, Kanikicharla, Kolli Rupa Kumar, R. G. Ashrit, N. R. Deshpande, and James William Hansen. 2004. "Climate Impacts on Indian Agriculture." *International Journal of Climatology: A Journal of the Royal Meteorological Society* 24 (11): 1375–93.

Krishnamurthy, Chandra Kiran B., Upmanu Lall, and Hyun-Han Kwon. "Changing Frequency and Intensity of Rainfall Extremes over India from 1951 to 2003." *Journal of Climate* 22 (18): 4737–46.

Krishnan R., T. P. Sabin, R. Vellore, M. Mujumdar, J. Sanjay, B. N. Goswami, F. Hourdin, J.-L. Dufresne, and P. Terray. 2016. "Deciphering the Desiccation Trend of the South Asian Monsoon Hydroclimate in a Warming World." *Climate Dynamics* 47 (3–4): 1007–27. https://doi.org/10.1007/s00382-015-2886-5.

Krishnan, Raghavan, Jayanarayanan Sanjay, Chellappan Gnanaseelan, Milind Mujumdar, Ashwini Kulkarni, and Supriyo Chakraborty, eds. 2020. *Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MOES), Government of India*. Singapore: Springer Nature.

Kumar, K. Krishna, Balaji Rajagopalan, Martin Hoerling, Gary Bates, and Mark Cane. 2006. "Unraveling the Mystery of Indian Monsoon Failure during El Niño." *Science* 314 (5796): 115–19.

Mahmood, Sana, Jemma Davie, Peter Jermey, Richard Renshaw, John P. George, E. N. Rajagopal, and S. Indira Rani. 2018. "Indian Monsoon Data Assimilation and Analysis Regional Reanalysis: Configuration and Performance." *Atmospheric Science Letters* 19 (3): e808. https://doi.org/10.1002/asl.808.

Mishra, Vimal, Amar Deep Tiwari, and Rohini Kumar. 2022. "A Framework to Incorporate Spatiotemporal Variability of Rainfall Extremes in Summer Monsoon Declaration in India." *Environmental Research Letters* 17 (9): 094039.

Mohanty, Abinash. 2020. *Preparing India for Extreme Climate Events: Mapping Hotspots and Response Mechanisms*. New Delhi: Council on Energy, Environment and Water.

Mohanty, Abinash, and Shreya Wadhawan. 2021. *Mapping India's Climate Vulnerability: A District-Level Assessment*. New Delhi: Council on Energy, Environment and Water.

Murray, Virginia, and Kristie L. Ebi. 2012. "IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)." *Journal of Epidemiology and Community Health* 66 (9): 759–60.

Pachauri, Rajendra K., Myles R. Allen, Vicente R. Barros, John Broome, Wolfgang Cramer, Renate Christ, John A. Church, et al. 2014. *Climate Change 2014: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.

Pai, D. S., M. Rajeevan, O. P. Sreejith, B. Mukhopadhyay, and N. S. Satbha. 2014. "Development of a New High Spatial Resolution (0.25 x 0.25) Long Period (1901-2010) Daily Gridded Rainfall Data Set over India and Its Comparison with Existing Data Sets over the Region." *Mausam* 65 (1): 1–18.

Philip, Shaju. 2023. "In Kerala Schools, Weather Stations to Make Geography Lessons Fun." *The Indian Express*, July 2, 2023. https://indianexpress.com/article/india/in-kerala-schools-weather-stations-to-make-geography-lessons-fun-8695821/#:~:text=station%20(SWS).-,For%20a%20little%20over%20a%20year%2C%20children%20in%20Kerala's%20schools,micro%2Dweather%20patterns%20and%20climate.

Rajeevan, Madhavan., M. Mohapatra, C. K. Unnikrishnan, B. Geetha, S. Balachandran, O. P. Sreejith, P. Mukhopadhyay, et al. 2022. *Northeast Monsoon of South Asia, Meteorological Monograph*. New Delhi: IMD, Ministry of Earth Sciences. https://mausam.imd.gov.in/imd_latest/contents/met_monograph.pdf.

Rajeevan, Madhavan, Jyoti Bhate, and Ashok K. Jaswal. 2008. "Analysis of Variability and Trends of Extreme Rainfall Events over India using 104 Years of Gridded Daily Rainfall Data." *Geophysical Research Letters* 35 (18). https://doi.org/10.1029/2008GL035143.

Rajesh, P. V., and B. N. Goswami. 2023. "Climate Change and Potential Demise of the Indian Deserts." *Earth's Future* 11 (8): e2022EF003459.

Roxy, Mathew Koll, Subimal Ghosh, Amey Pathak, R. Athulya, Milind Mujumdar, Raghu Murtugudde, Pascal Terray, and M. Rajeevan. 2017. "A Threefold Rise in Widespread Extreme Rain Events over Central India." *Nature Communications* 8 (1): 708.

Sabade, S., A. Kulkarni, and R. Kripalani. 2011. "Projected Changes in South Asian Summer Monsoon by Multi-Model Global Warming Experiments." *Theoretical and Applied Climatology* 103 (3–4): 543–65. https://doi.org/10.1007/s00704-010-0296-5.

Saha, A., S. Ghosh, A. S. Sahana, and E. P. Rao. 2014. "Failure of CMIP5 Climate Models in Simulating Post-1950 Decreasing Trend of Indian Monsoon." *Geophysical Research Letters* 41:7323–30. https://doi.org/10.1002/2014GL061573.

Sanyal, Prasanta, and R. Sinha. 2010. "Evolution of the Indian Summer Monsoon: Synthesis of Continental Records." *Geological Society, London, Special Publications* 342 (1): 153–83.

Shagun, Himanshu Nitnaware. 2022. "Update Overdue: Why Climate Change Should Be Integrated into Crop Calendars at the Hyper-Local Level." *DownToEarth*, September 10. https://www.downtoearth.org.in/news/agriculture/update-overdue-why-climate-change-should-be-integrated-into-crop-calendars-at-the-hyper-local-level-84806.

Sharmila, S., S. Joseph, A. K. Sahai, S. Abhilash, and R. Chattopadhyay. 2015. "Future Projection of Indian Summer Monsoon Variability under Climate Change Scenario: An Assessment from CMIP5 Climate Models." *Global and Planetary Change* 124:62–78. http://dx.doi.org/10.1016/j.gloplacha.2014.11.004.

Shukla, J., and D. A. Mooley. 1987. "Empirical Prediction of the Summer Monsoon Rainfall over India." *Monthly Weather Review* 115 (3): 695–704.

Sikka, D. R., and Sulochana Gadgil. 1980. "On the Maximum Cloud Zone and the ITCZ over Indian Longitudes during the Southwest Monsoon." *Monthly Weather Review* 108 (11): 1840–53.

Singh, Tarkeshwar, Upal Saha, V. S. Prasad, and Munmun Das Gupta. 2021. "Assessment of Newly-Developed High Resolution Reanalyses (IMDAA, NGFS and ERA5) against Rainfall Observations for Indian Region. *Atmospheric Research* 259:105679. https://doi.org/10.1016/j.atmosres.2021.105679.

The Economic Times. 2021. "Maharashtra Govt Announces Rs 10,000 cr Aid for Rain-Affected Farmers." 2021. *The Economic Times*, October 13. https://economictimes.indiatimes.com/news/india/maharashtra-govt-announces-rs-10000-cr-aid-for-rain-affected-farmers/articleshow/86992689.cms?from=mdr.

The Times of India. 2022. "Gujarat Govt Announces Rs 630 Crore Relief Package for Rain-Affected Farmers in 14 Districts." *The Times of India*, October 28. https://timesofindia.indiatimes.com/city/ahmedabad/gujarat-govt-announces-rs-630-crore-relief-package-for-rain-affected-farmers-in-14-districts/articleshow/95145957.cms.

Trenberth, Kevin E. 1999. "Conceptual Framework for Changes of Extremes of the Hydrological Cycle with Climate Change." *Climatic Change* 42 (1): 327–39.

Turner, A. G., and J. M. Slingo. 2009. "Subseasonal Extremes of Precipitation and Active-Break Cycles of the Indian Summer Monsoon in a Climate Change Scenario." *Quarterly Journal of the Royal Meteorological Society* 135 (640): 549–67. https://doi.org/10.1002/qj.401.

Varikoden, Hamza, and J. V. Revadekar. 2020. "On the Extreme Rainfall Events during the Southwest Monsoon Season in Northeast Regions of the Indian Subcontinent." Meteorological Applications 27 (1): e1822.

Vittal, Hersha, Subhankar Karmakar, and Subimal Ghosh. 2013. "Diametric Changes in Trends and Patterns of Extreme Rainfall over India from Pre-1950 to Post-1950." Geophysical Research Letters 40 (12): 3253–58.

Wang, Bin, Sulochana Gadgil, and K. Rupa Kumar. 2006. "The Asian Monsoon – Agriculture and Economy." In The Asian Monsoon, edited by Bin Wang, 651–83. Berlin: Springer Berlin, Heidelberg.

Wang, Chien, Dongchul Kim, Annica M. L. Ekman, Mary C. Barth, and Phillip J. Rasch. 2009. "Impact of Anthropogenic Aerosols on Indian Summer Monsoon." Geophysical Research Letters 36 (21). https://doi.org/10.1029/2009GL040114.

WMO. 2017. WMO Guidelines on the Calculation of Climate Normals. Geneva: World Meteorological Organization.

WMO. 2023. "Global Temperatures Set to Reach New Records in the Next Five Years" [Press release]. World Meteorological Organization, May 17. https://public.wmo.int/en/media/press-release/global-temperatures-set-reach-new-records-next-five-years.

WMO. n.d. "State of the Global Climate: Asia – 2022." World Meteorological Organization. Accessed October 11, 2023. https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate/Asia-2022.

Yasunari, Tetsuzo. 1979. "Cloudiness Fluctuations Associated with the Northern Hemisphere Summer Monsoon." Journal of the Meteorological Society of Japan Ser. II 57 (3): 227–42.

The authors

Shravan Prabhu
shravan.prabhu@ceew.in I 𝕏@Shravanverse

Shravan is a research analyst with the Council's Climate Resilience team. His research focuses on harnessing extensive climate and geospatial data to evaluate chronic and acute climate risks across vital sectors, including energy, agriculture, water, health, and industries. His research actively contributes to the development of sub-national climate action plans and the creation of risk-informed decision-making tools. Additionally, he works on mainstreaming climate risk disclosures and fostering the adoption of resilience tools, such as climate risk insurance.

Vishwas Chitale
vishwas.chitale@ceew.in I 𝕏@Vishchi

Vishwas leads the Climate Resilience team at the Council, where his work focuses on assessing risks and building resilience. He has over 15 years of experience in developing and implementing digital solutions for climate change risk reduction and resilience building in various South Asian countries. He previously worked on AI for Climate Change and on assessing vulnerability of forest ecosystems. Vishwas holds a PhD in 'Assessing climate change impacts on biodiversity hotspots in India' from the Indian Institute of Technology Kharagpur, and he has published more than 35 peer-reviewed articles, 10+ blogs and book chapters.

The monsoon rains have different names in different states in India. For instance, it is called 'Mungaaru Male' in Kannada and 'Merku Paruva Malai' in Tamil.

Image: Alamy

COUNCIL ON ENERGY, ENVIRONMENT AND WATER (CEEW)

ISID Campus, 4 Vasant Kunj Institutional Area
New Delhi - 110070, India
T: +91 (0) 11 4073 3300

info@ceew.in | ceew.in | 𝕏@CEEWIndia | ceewindia