



# Changing Patterns of Summer Monsoon over North-West India

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**Abstract**— Actually, the monsoon is a seasonal process formed due to the shifting of the Inter-Tropical Convergence Zone (ITCZ) over the Tropic of Cancer during summer. India's summer monsoon is a lifeline for its agriculture, economy, and overall sustenance. A successful monsoon season brings growth, stability, and prosperity, while a failed one can lead to drought, hunger, and economic hardship. Understanding monsoon is essential for managing agriculture, water resources, and disaster preparedness in affected regions. Despite ongoing research, there remains a limited understanding of the underlying causes and regional-scale manifestations of these changing rainfall patterns. This study aims to address these gaps by analyzing the spatial and temporal changes in summer monsoon rainfall over North-West (NW) India and identifying possible climatic drivers behind these shifts.



**Keywords**— agriculture, summer monsoon, rainfall patterns, remote sensing data, climatic drivers, ITCZ.

## I. INTRODUCTION

A monsoon is not just a rainstorm; it is a seasonal wind system that affects climate and agriculture in many parts of the world. The monsoon is a vital natural system that brings both life-sustaining rain and potential challenges. The monsoon is a seasonal weather phenomenon characterized by a reversal of wind direction and a significant change in precipitation patterns. It typically brings heavy rainfall to large regions, especially in tropical and subtropical areas.

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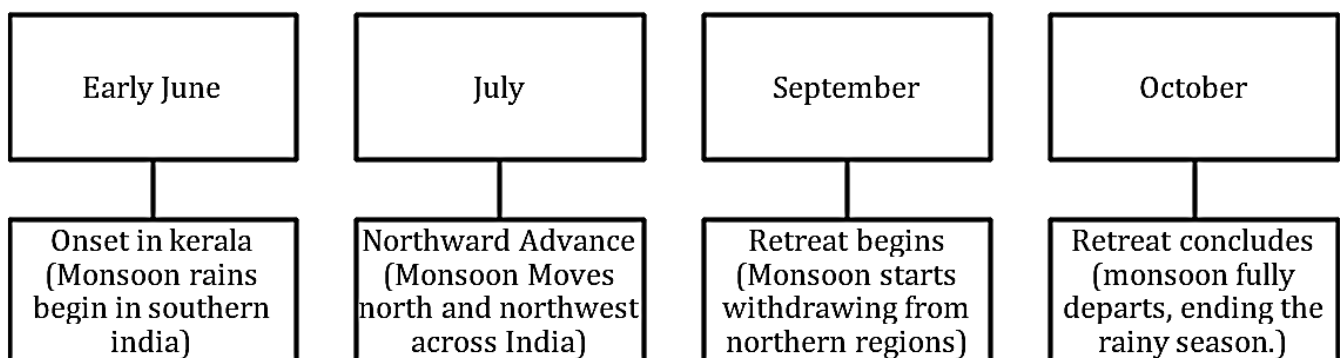


Fig. 1: Indian Monsoon Season Timeline

The summer monsoon rainfall pattern in Northwest India has undergone significant changes in recent decades, exhibiting both an increase in total precipitation and greater spatial variability. In 2025, Northwest India experienced its highest seasonal monsoon rainfall, recording about 127 percent of the long period average since 2001, driven by shifts in monsoon onset, intensity, and distribution. These changes are linked to evolving atmospheric circulation patterns, earlier and more rapid monsoon onset, higher frequency of monsoon depressions, and larger variability across meteorological subdivisions. The new rainfall regime has important implications for agriculture, water management, and climate resilience in the region.

The key drivers of the changing monsoon pattern in Northwest India are rapid warming of the Indian Ocean, expansion of the Hadley Cell, shifts in upper atmospheric circulation linked to the Silk Road pattern and Tibetan Plateau, and more frequent monsoon depressions in the North Arabian Sea. These factors collectively result in stronger moisture transport and altered wind dynamics, leading to increased and more variable rainfall in Northwest India over recent decades.

India receives approximately 80 percent of its total rainfall during the Indian Summer Monsoon (ISM) season, from June through September. The timing and intensity of ISM rainfall play a significant role in shaping the country's economy. Extreme rainfall events have tripled in India since 1950. Indian Summer Monsoon rainfall exhibits temporal variability spanning intra-seasonal to multi-decadal time scales, and it involves complex interactions between different factors.

These changes can be attributed to an increase in the frequency of monsoon depressions by about 46 percent over the Arabian Sea, while the Bay of Bengal has experienced about 32 percent decrease.

## II. STATEMENT OF THE PROBLEM

The summer monsoon is a critical source of water for agriculture, ecosystems and water resources in NW India. However, in recent decades, this region has experienced significant changes in the pattern, distribution, and intensity of monsoon rainfall. These changes include increased variability, shifts in onset and withdrawal dates, more frequent extreme rainfall events, and longer dry spells. Such variations directly impact agricultural productivity, groundwater recharge, and the overall socio-economic stability of the region, which is already characterized by arid and semi-arid conditions.

Despite ongoing research, there remains a limited understanding of the underlying causes and regional-scale

manifestations of these changing rainfall patterns. Additionally, discrepancies between different datasets, including in-situ observations, remote sensing data, and re-analysis products, complicate efforts to detect long-term trends and make reliable predictions. This study aims to address these gaps by analyzing the spatial and temporal changes in summer monsoon rainfall over NW India and identifying possible climatic drivers behind these shifts.

## III. RESEARCH OBJECTIVES

- > To analyze the temporal trends in summer monsoon rainfall over NW India using long-term observational, remote sensing and re-analysis datasets.
- > To assess spatial variations in rainfall distribution and intensity during the monsoon season across different parts of NW India.
- > To detect changes in the onset, duration and withdrawal of the summer monsoon over recent decades.
- > To identify the frequency and magnitude of extreme rainfall events (e.g., heavy rainfall days, dry spells) and their changing patterns over time.
- > To compare and validate different precipitation datasets (in situ, satellite-based and re-analysis) to improve reliability in rainfall trend analysis.
- > To investigate potential climatic drivers and atmospheric circulation patterns (e.g., ENSO, IOD, Western Disturbances) influencing monsoon variability in the region.
- > To evaluate the potential implications of changing monsoon patterns on agriculture, water resources and regional climate resilience strategies.

## IV. CONCEPTUAL FRAMEWORK

### 4.1. Climatic Drivers (External Forcings and Natural Variability):

These influence the large-scale atmospheric and oceanic systems that affect monsoon dynamics.

Category	Key Elements
Oceanic Drivers	Indian Ocean warming, Arabian Sea SST rise, Indian Ocean Dipole (IOD)
Atmospheric Circulation	Strengthened cross-equatorial flow, expansion of Hadley cell, changes in monsoon trough

Global Teleconnection	El-Nino/La-Nina–Pacific Decadal Oscillation, Madden–Julian Oscillation
Land surface changes	Irrigation expansion, Deforestation, Urbanization.

#### 4.2. Atmospheric Processes and Mechanisms:

These processes mediate how the above drivers influence rainfall patterns.

Process	Description
Moisture Transport	Increased moisture from Arabian Sea, enhanced convergence over N.W.
Monsoon Depressions and Lows	More frequent westward-tracking systems from Bay of Bengal/Arabian Sea.
Upper-Air Dynamics	Strengthening of 100-level jets, Rossby waves affecting NW India's rainfall patterns.
Rainfall Intensity Dynamics	Rise in heavy rainfall days, shorter but intense spells.
Delayed/Erratic Onset	Increasing variability of onset and withdrawal dates.

#### 4.3. Observed Changes in NW India (1979–Present):

Aspect	Observed Trend
Rainfall Amount	~30–40 percent increase over parts of NW India (especially Rajasthan, Punjab)
Rainfall Distribution	More uneven, higher intensity, fewer rainy days
Rainfall Duration	Compressed rainy season in some areas
Rainfall Extremes	Increase in extreme rainfall events & flash floods
Spatial Shift	Monsoon core zone expanding westward towards NW India

#### 4.4. Impacts on NW India:

Sector	Implications
Agriculture	Unpredictable sowing seasons, crop damage due to extremes, stress on irrigation scheduling

Water Resources	Increased runoff but lower groundwater recharge, overload of reservoirs and urban drains
Disaster Risk	Rise in flash floods, droughts from intra-seasonal dry spells
Socioeconomic	Food security threats, migration and rural vulnerability

## V. DATA INTERPRETATION

Over the last few decades, NW India has seen a clear upward trend in summer monsoon rainfall, especially in certain sub-regions with about a 40 percent increase from 1979–2022 compared to the 1980s.

### 5.1. Temporal Trends (1901–2024):

#### → Long-term trend–

Early 20th century: Stable or slightly decreasing rainfall.

Post-1970s: Increase in interannual variability

(years of extreme surplus or deficit).

Post-2000s: Signs of moderate increase in total monsoon rainfall over some parts of NW India (e.g., Punjab, Haryana), but decrease in others (e.g., western Rajasthan, Delhi National Capital Region).

Overall finding: The spatial distribution of monsoon rainfall is changing, even if overall rainfall remains similar.

#### Shift in peak months–

Traditionally, July and August were peak rainfall months.

↳ Recent data (e.g., IMD 2023 reports) suggest July rainfall has increased, while August rainfall has decreased.

For example, average August rainfall in NW India has declined by about 12% over the past 70 years.

### 5.2. Rainfall Variability and Extremes:

#### Higher rainfall variability–

Increase in short-duration, high intensity rainfall events.

Decrease in number of rainy days, meaning rain is coming in fewer but more intense spells.

This can cause flooding, even if seasonal rainfall totals are average.

#### Deficit vs excess years–

More frequent ‘monsoon breaks’ (dry spells during monsoon season).

Some states (e.g., Rajasthan, Delhi) are witnessing alternating years of floods and droughts.

### 5.3. Regional Disparities in Rainfall Trends:

State/Region	Observed Changes in Monsoon Rainfall
Punjab and Haryana	↑ Slight increase (especially July)
Delhi and NCR	↓ Decrease, erratic pattern
Rajasthan (west)	↓ long-term decline
Himachal Pradesh	↑ Increase, more intense spells
Western Uttar Pradesh	→ Near-normal but with high variability.

NW India is not a uniform block—different states show different rainfall patterns, largely due to topography, land-use and urbanization.

### 5.4. Contributing Factors to Pattern Changes:

Climate change—warming of Arabian Sea/Indian Ocean.

Hadley cell expansion.

Urbanization.

Deforestation and land-use change.

### 5.5. Rainfall Trends:

North West India rainfall trends by decade show a clear variability and recent increases, especially after the 2000s. Analysis of datasets from national and open data sources highlights the following:

**Decadal Rainfall Trends in NW India is given hereunder from 1901 to 2025:**

Decade(s)	Observed Trend
1901 – 1910	Baseline, minor fluctuations
1911 – 1940	Slight long-term decline
1941 – 1970	Modest upward shifts
1971 – 2000	Relative stability, variability
2001 – 2010	Marked increases start, erratic
2011 – 2020	Increasing anomalies, volatile
2021 – 2025	Strong positive anomaly, record highs.

### 5.6. Summary Interpretation:

Indicator	Pattern Observed
Total Monsoon Rainfall	Slight up in some areas, down in others
Number of rainy days	↓ Decreasing
Intensity of Rainfall	↑ Increasing
Month-wise distribution	Shift from August to July in many areas
Regional uniformity	↓ Becoming more uneven
Extreme events (flood/drought)	↑ More frequent and intense

The summer monsoon in NW India is becoming more erratic and intense, with a shift in peak months, a drop in rainy days and more uneven regional distribution. This is consistent with broader climate change patterns and is already impacting agriculture, water resources and disaster relief management.

### 5.7. Key Statistics:

Seasonal rainfall over NW India, Central India and south peninsula were 27, 15, and 10 percent respectively more than their seasonal averages, this year. India received 8 percent more monsoon rain this year than normal.

2025 Monsoon Rainfall (June–Sept.): 747.9 mm (NW India), normal 587.6 mm, 27 percent surplus.

2023 Monsoon = 1 percent surplus over normal; 2024–7 percent surplus.

Trend = Highest NW rainfall since 2001, 6th highest since 1901.

Dataset sources—IMD, Kaggle—historic and recent monsoon rainfall statistics for NW India, Dataful.in, Recent press releases and Reports and latest decades data, 2023–2025 statistics.

## VI. CONCLUSION

The analysis of long-term rainfall data over NW India reveals clear evidence of changing patterns in summer monsoon rainfall. While the total seasonal rainfall over some parts of the region has shown significant increases (notably in Punjab and parts of Haryana), others have experienced a decline or increased variability.

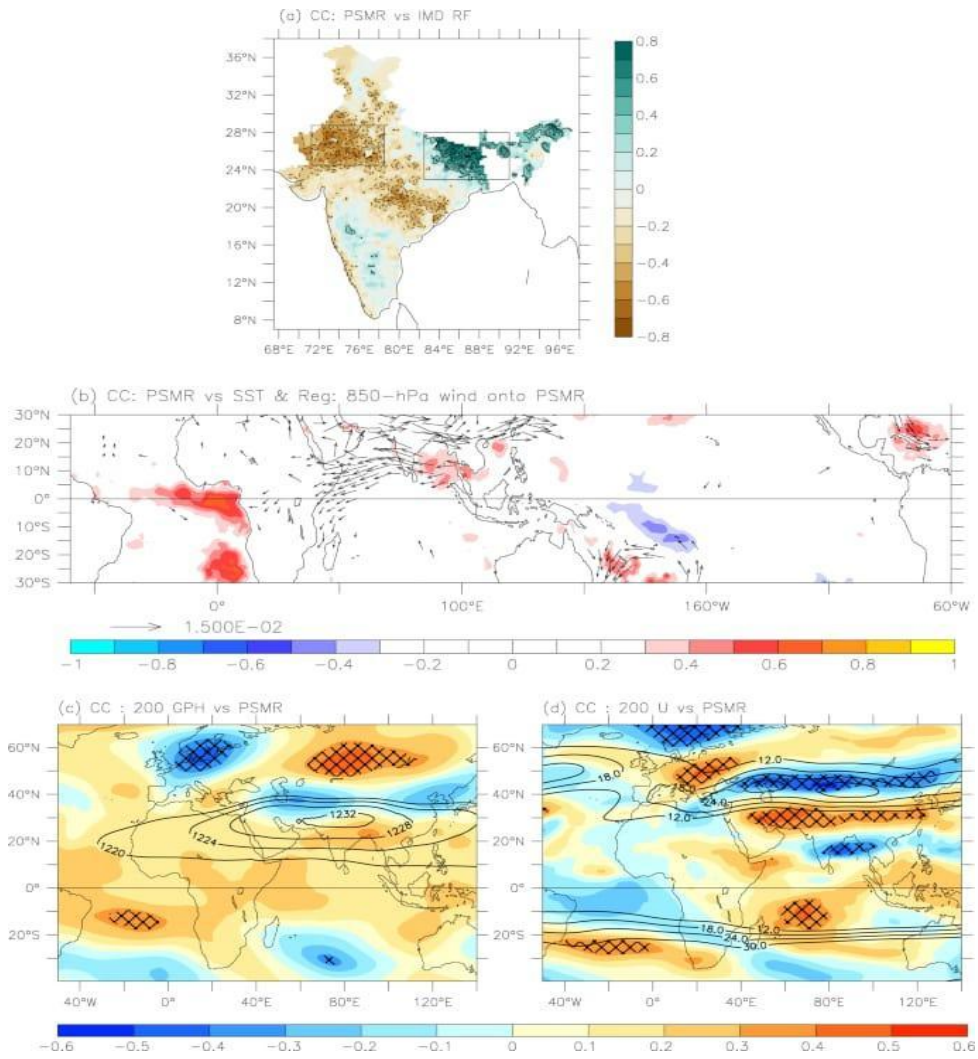


Fig.2

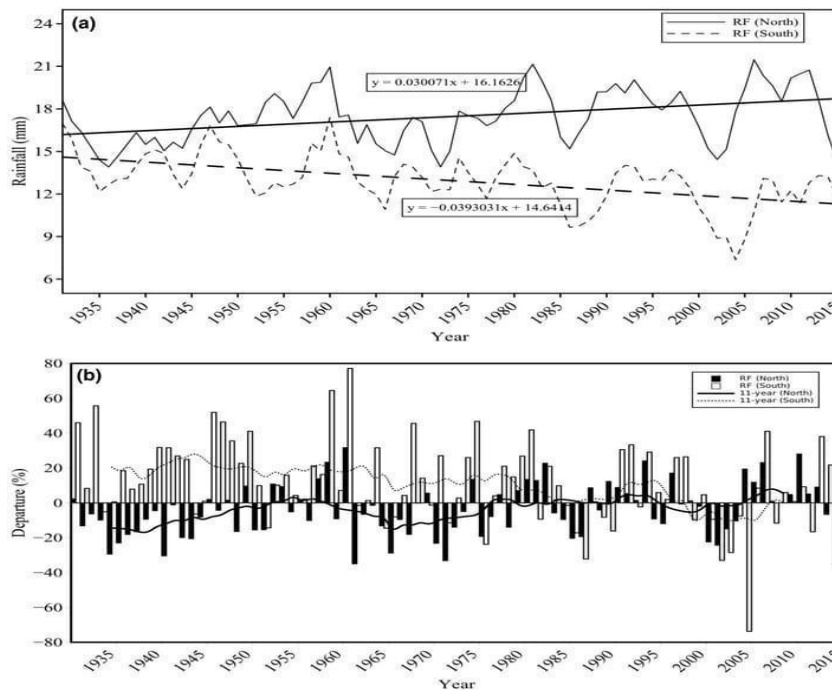


Fig.3

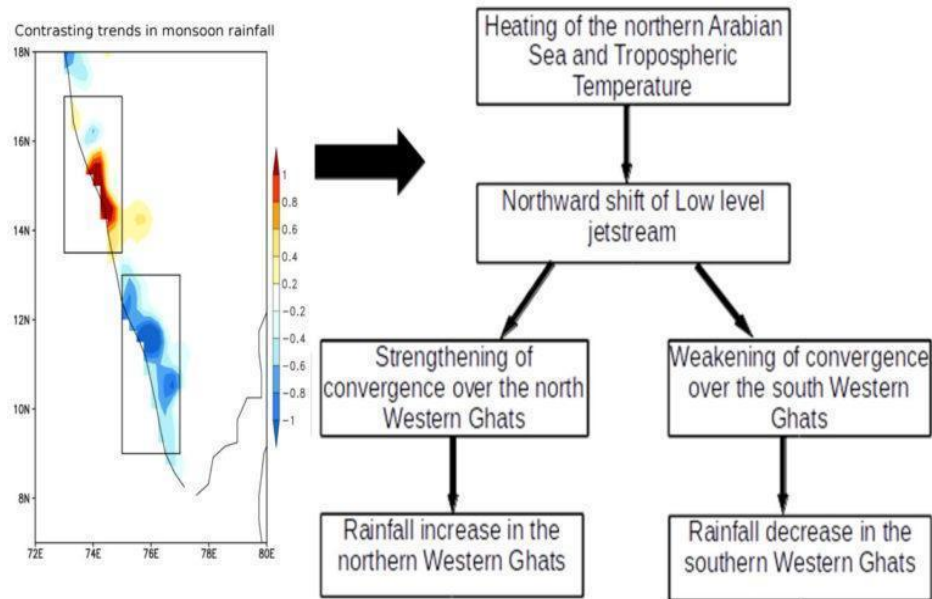


Fig.4

One of the most significant changes observed is the shift in intra-seasonal distribution of rainfall. Traditionally, wet months like August have seen a gradual decline in rainfall, whereas July has become wetter, altering the timing and reliability of agricultural activities. Moreover, the number of rainy days has decreased, even though the frequency of high-intensity rainfall events has increased, especially in urban and hilly areas. This points to intense rainfall spells, which have greater potential to cause flash floods, urban waterlogging and crop damage.

These shifts in the monsoon pattern are likely driven by a complex interplay of factors, including climate change, warming of the Indian Ocean, Hadley cell expansion, aerosol loading and changes in land cover.

## VII. KEY FINDINGS

- Summer monsoon rainfall patterns are becoming more erratic and regionally uneven.
- Rainfall intensity is increasing, but rainfall duration and frequency are decreasing.
- Certain months (especially August) are receiving less rainfall over time.
- The spatial spread of rainfall has shifted, with implications for regional water management and agriculture.

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