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Temporal Evolution of Dominant Periodicity in All India and Kerala Monsoon Rainfall (1901-2024): A Comparative Spectral Analysis

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Abstract. Understanding the temporal organization of monsoon rainfall variability is essential for characterizing long-term climatic behavior over the Indian subcontinent. This study investigates the dominant periodicities in All-India and Kerala annual monsoon rainfall using long-term observational records spanning 1901–2024. Fast Fourier Transform (FFT) analysis is applied to the complete datasets to identify primary variability scales. To assess potential non-stationarity, the 124-year record is divided into three equal epochs and examined through epoch-wise spectral analysis. The results reveal that All-India rainfall exhibits pronounced temporal shifts in dominant periodicities, transitioning from interannual (~2–3 years) variability in the early twentieth century to decadal (~8–14 years) dominance in subsequent epochs. In contrast, Kerala rainfall demonstrates persistent decadal-scale variability throughout the record, with a gradual increase in dominant periodicity from approximately 10 years to around 14 years across successive epochs. The complete Kerala dataset further indicates a prominent quasi-decadal to multi-decadal peak (~17–18 years), underscoring the importance of longer-term oscillatory components at the regional scale. The comparative spectral analysis demonstrates clear regional contrasts in the temporal organization of monsoon rainfall variability. While the aggregated All-India rainfall series reflects evolving and non-stationary dominant periodicities, the Kerala record maintains relatively stable decadal-scale dominance. This contrast suggests that national-scale rainfall integrates multiple time-varying variability modes, whereas regional rainfall may preserve more persistent oscillatory characteristics. Overall, the findings provide statistical evidence of structural evolution in dominant variability scales and contribute to improved understanding of the evolving multi-scale behavior of Indian monsoon rainfall.

Keywords: spectral analysis; Fast Fourier Transform; Indian monsoon; Kerala rainfall; climate variability

Introduction

The Indian summer monsoon is one of the most complex and influential components of the global climate system. It governs the hydrological cycle over the Indian subcontinent and sustains nearly one-sixth of the world's population through its control on agriculture, water resources, and ecosystem stability. Approximately 75–80% of the annual rainfall over India is received during the monsoon season (June–September), making its variability a critical determinant of food security and economic stability [1][2]. Even modest deviations from normal rainfall can lead to widespread droughts or floods, emphasizing the importance of understanding its temporal behavior. Indian monsoon rainfall exhibits variability across multiple temporal scales, ranging from year-to-year fluctuations to decadal and longer-term oscillations. Interannual variability has been extensively studied in relation to large-scale climate interactions and circulation dynamics. In addition to interannual fluctuations, several studies have documented decadal and multi-decadal variations in monsoon rainfall, suggesting the presence of longer-term modulation mechanisms. Such variability highlights the inherently multi-scale nature of the monsoon system and underscores the need for systematic temporal characterization.

Time-series and spectral analysis techniques have been widely employed in climate research to identify dominant oscillatory components embedded within meteorological datasets. Fourier-based methods allow decomposition of a signal into frequency components, thereby providing insight into the underlying temporal structure of variability. In atmospheric sciences, spectral analysis has proven useful for detecting dominant variability scales and assessing structural organization in long climatic records. However, many previous investigations have focused either on seasonal rainfall totals, specific teleconnection mechanisms [3][4], or trend detection, with comparatively limited emphasis on systematic examination of century-long annual rainfall records using epoch-wise spectral comparison.

An important consideration in climate variability studies is the potential non-stationarity of dominant oscillatory modes. Climate systems are dynamic [5], and variability scales identified during one period may evolve over time due to changing background conditions. Several investigations have reported temporal shifts in monsoon variability characteristics across decades, suggesting that dominant periodicities may not remain constant over extended records. Nevertheless, comprehensive epoch-wise spectral assessment over long-term rainfall datasets remains relatively limited. Moreover, most spectral investigations in the Indian context emphasize All-India aggregated rainfall, which represents a spatially integrated measure across diverse climatic zones. While this index provides a valuable large-scale indicator of monsoon behaviour, aggregation may obscure region-specific variability patterns. Regional rainfall, influenced by localized topography, coastal dynamics, and circulation features, may exhibit distinct temporal structures. Kerala, located along the southwestern coast of India and recognized as the onset region of the summer monsoon, provides a climatically significant case for regional comparison. Comparative spectral assessment between national and regional rainfall over extended historical periods remains comparatively underexplored.

In this context, the present study investigates the temporal evolution of dominant periodicities in All-India and Kerala annual monsoon rainfall for the period 1901–2024. Fast Fourier Transform (FFT) analysis is applied to the complete datasets to identify primary variability scales. To evaluate potential non-stationarity, the 124-year record is divided into three equal epochs, and spectral characteristics are examined separately for each segment. The objectives of this study are: (i) to identify dominant periodicities in All-India and Kerala rainfall; (ii) to assess epoch-wise changes in these periodicities; and (iii) to compare national and regional variability structures to examine differences in temporal organization.

The remainder of the paper is organized as follows. Section 2 presents a detailed review of relevant literature. Section 3 describes the dataset and the methodology framework. Section 4 presents and analyses the results of complete and epoch-wise spectral analyses for All-India and Kerala rainfall and Section 5 concludes the study.

2. Literature Review

2.1. Interannual and Decadal Variability of Indian Monsoon Rainfall

Indian monsoon rainfall exhibits variability across multiple temporal scales [6]. Interannual variability and its socio-economic implications have been widely documented, particularly in relation to large-scale atmospheric and oceanic interactions. In addition to year-to-year fluctuations, several studies have reported decadal and multi-decadal [7][8][9] modulations in monsoon rainfall. Increasing variability in extreme rainfall events further indicates evolving characteristics in monsoon behavior. Collectively, these findings demonstrate that monsoon rainfall variability is

inherently multi-scale and potentially non-stationary.
However, much of the earlier research emphasizes trend detection [10][11] or teleconnection mechanisms with comparatively limited focus on systematic identification of dominant periodicities across extended century-long rainfall datasets. Explicit spectral characterization is therefore necessary to better understand the temporal structure and evolution of variability modes.

2.2. Spectral and Time-Series Approaches in Climate Research

Spectral analysis has been widely applied in climate research to detect oscillatory components embedded within time-series data. Classical Fourier-based approaches allow decomposition of a signal into frequency components and identification of dominant periodicities. In atmospheric sciences, spectral methods have been used to analyse rainfall and circulation datasets across multiple temporal scales. Despite advances in time-frequency techniques, the Fast Fourier Transform (FFT) [12][13] remains a fundamental tool for identifying primary variability scales in long climatic records.

2.3. Regional Versus National Rainfall Variability

All-India rainfall [14][15] represents an area-averaged index integrating diverse climatic zones. While it provides a large-scale indicator of monsoon behavior, aggregation may mask regional variability characteristics. Regional rainfall is influenced by localized topography and coastal dynamics, potentially producing distinct temporal structures.

The southwestern coastal state of Kerala experiences some of the earliest monsoon rainfall in India and therefore provides an important regional perspective for examining monsoon variability. Several studies have examined rainfall variability and extreme events in this region. However, most existing investigations [16] primarily focus on long-term trends or seasonal behavior rather than analyzing the spectral characteristics of rainfall variability or comparing it directly with the All-India rainfall index over long historical periods. Understanding differences in dominant periodicities between national and regional rainfall indices is therefore important for assessing spatial heterogeneity in monsoon variability.

2.4. Non- Stationarity

Climate variability is increasingly recognized as non-stationary [17][18], with dominant modes evolving across decades.Variability scales identified in one period may not persist in subsequent periods. Nevertheless, explicit epoch-wise spectral assessment of century-scale rainfall datasets to evaluate structural evolution remains insufficiently explored.

Two key gaps are evident from the literature. First, systematic identification and comparison of dominant periodicities across successive temporal epochs within long rainfall records remain limited. Second, comparative spectral evaluation between aggregated All-India rainfall and climatically significant regional rainfall such as Kerala has received relatively less attention. The present study addresses these gaps through a comparative epoch-wise spectral investigation of All-India and Kerala rainfall for the period 1901–2024.

Methodology

1.1. Data Description

Annual rainfall data for the period 1901–2024 were obtained from the India Meteorological Department for two spatial domains: (i) All-India rainfall and (ii) Kerala rainfall. The datasets consist of continuous annual totals suitable for long-term variability analysis.

1.2. *Temporal Segmentation*

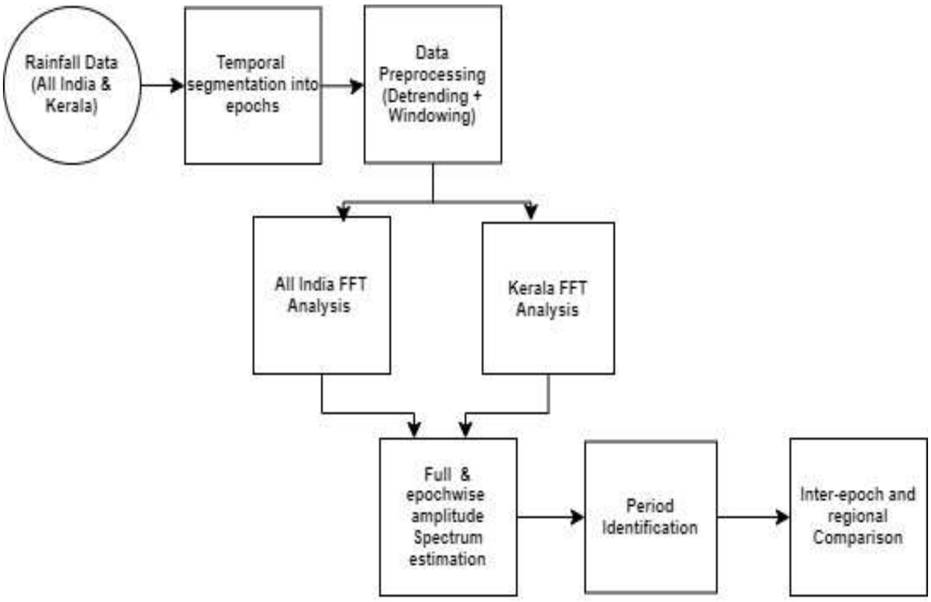


Figure 1: Schematic representation of the methodological framework for spectral analysis of All-India and Kerala rainfall (1901–2024)

To examine the temporal evolution of rainfall variability, the 124-year record was divided into three approximately equal epochsas shown in figure 1. Spectral analysis was carried out for:

- The complete period (1901–2024)
- Epoch I (1901–1941(41 years)
- Epoch II (1942–1982 (41 years)
- Epoch III (1983–2024 (42 years)

This segmentation enables assessment of changes in dominant periodicities across different time intervals.

1.3. *Preprocessing of Rainfall Series*

Prior to spectral analysis, preprocessing steps were applied to ensure reliable frequency-domain estimation.

(i) Linear Detrending

Linear detrending [19] was performed to remove long-term linear trends from the rainfall time series. This step ensures that the spectral analysis primarily captures oscillatory variability rather than trend-related low-frequency energy.

(ii) Hanning Window Application

A Hanning window [20] was applied to the detrended series to minimize spectral leakage resulting from the finite length of the data. This reduces artificial spreading of spectral energy across adjacent frequencies.

1.4. *Fast Fourier Transform (FFT)*

The Fast Fourier Transform (FFT) was applied to the windowed rainfall series to compute the frequency spectrum. The amplitude spectrum was obtained from the magnitude of the Fourier coefficients. Due to the symmetry of the Fourier transform for real-valued signals, only positive frequency components were retained for analysis.

1.5. *Frequency-to-Period Conversion*

To facilitate interpretation in climatological terms, frequency values were converted into periods (in years). This allows identification of dominant variability scales such as interannual and decadal oscillations.

1.6. *Epoch-wise and Regional Spectral Analysis*

The FFT procedure was applied independently to:

- All-India rainfall (complete period and three epochs)
- Kerala rainfall (complete period and three epochs)

Dominant periodicities were identified as the periods corresponding to the maximum amplitude in the spectrum. Comparative analysis was performed to examine:

- Differences between All-India and Kerala rainfall variability
- Shifts in dominant periodicities across epochs
- Changes in the distribution of spectral energy over time

Results and Discussion

1.7. *Spectral Characteristics of All-India Rainfall*

The All-India annual rainfall series was analyzed in the frequency domain to examine the distribution of variability across different temporal scales. Both the complete 124-year record and its three temporal epochs were evaluated to identify dominant periodic components and assess their evolution over time.

4.1.1 Complete Period (1901–2024)

The amplitude spectrum of the complete All-India rainfall record is presented in Figure 2. The spectrum exhibits distinct peaks in both the interannual and decadal bands, with prominent energy concentrations around ~2–3 years and within the ~8–14-year range. These features indicate the coexistence of short-term and longer-term oscillatory behavior in the aggregated rainfall signal.

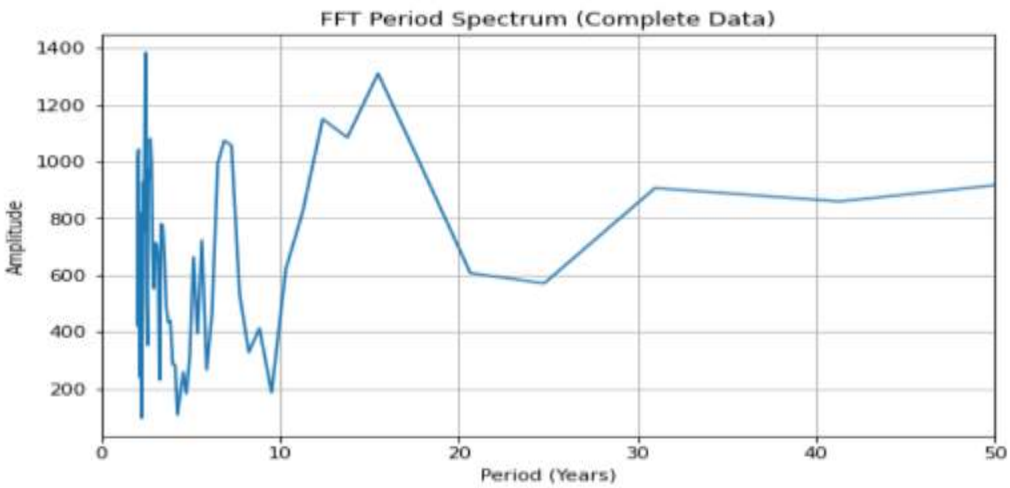


Figure 2. Amplitude spectrum (period vs amplitude) of All-India annual rainfall (1901–2024).

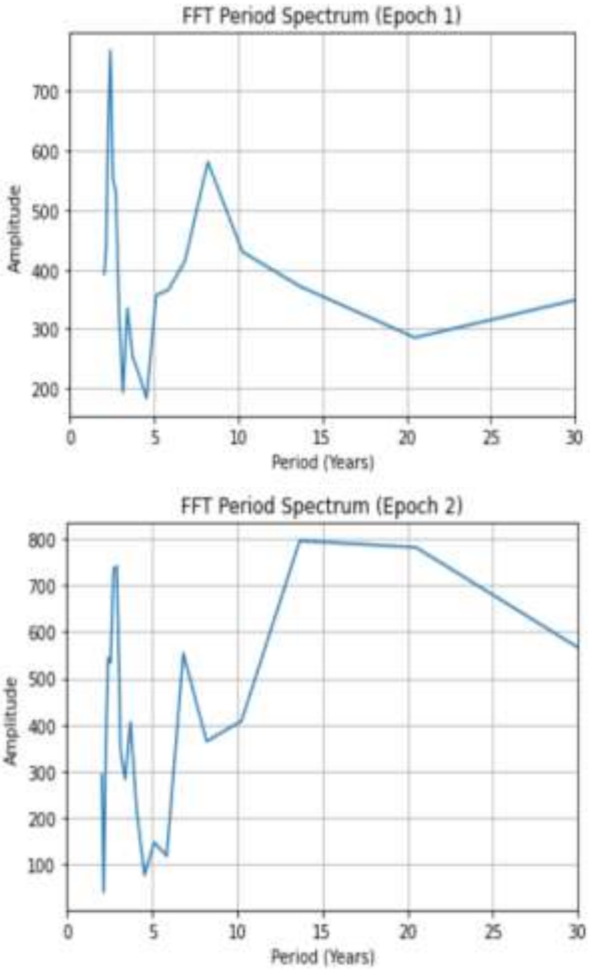
The dominant periodicity is identified at **2.48 years**, corresponding to the maximum spectral amplitude (**1383.91**), confirming the predominance of interannual variability over the full study period.

4.1.2 Epoch-wise Spectral Analysis

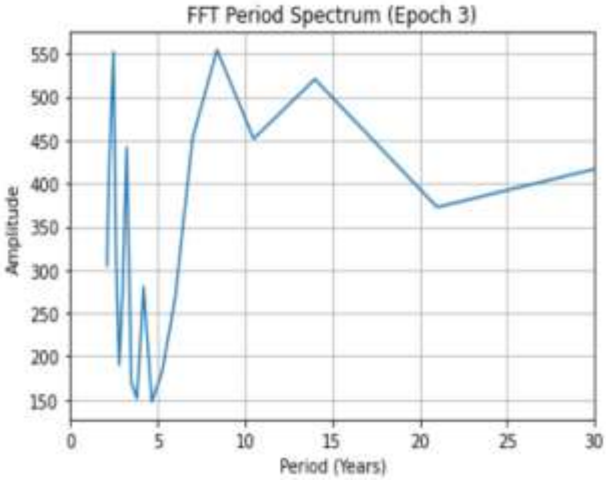
To assess temporal evolution, the dataset was divided into three equal epochs, and the corresponding amplitude spectra are shown in Figure 3. A clear shift in dominant periodicity is observed across epochs.

Epoch I (1901–1941) is characterized by a dominant period of **2.41 years**, consistent with the interannual dominance observed in the complete record. In contrast, Epoch II (1942–1982) exhibits a marked shift toward a longer-period oscillation of **13.67 years**, indicating enhanced decadal-scale variability during the mid-twentieth century. During Epoch III (1983–2024), the dominant periodicity transitions to **8.40 years**, reflecting intermediate-scale variability in recent decades.

The abrupt increase from ~2.4 years (Epoch I) to ~13.7 years (Epoch II), followed by a reduction to ~8.4 years (Epoch III), indicates pronounced non-stationarity in the All-India rainfall variability structure.



(a) (b)



(c)

Figure 3. Epoch-wise amplitude spectra of All-India rainfall: (a) Epoch 1, (b) Epoch 2, (c) Epoch 3.

The dominant periodicities and corresponding maximum amplitudes for the complete period and individual epochs are summarized in Table1. The table further demonstrates redistribution of spectral energy across time scales, highlighting evolving rainfall dynamics over the twentieth and early twenty-first centuries.

Table 1: Dominant periodicities and corresponding maximum amplitudes of All-India annual rainfall for the complete period (1901–2024) and individual epochs.

Duration	**Dominant period (Years)**	**Amplitude**
Complete Data: 1901-2024 (124 years)	2.48 years	1383.9072
Epoch 1: 1901–1941(41 years)	2.411765	768.188780
Epoch 2: 1942–1982 (41 years)	13.666667	796.001431
Epoch 3: 1983–2024 (42 years)	8.400000	554.117117

Collectively, these results indicate that the dominant variability scale of All-India rainfall has not remained temporally stable over the 124-year record. Instead, the rainfall system exhibits distinct shifts between interannual and decadal dominance across successive epochs, reflecting evolving oscillatory characteristics in the monsoon variability structure.

1.8. Spectral Characteristics of Kerala Rainfall

To investigate the dominant temporal scales embedded in Kerala rainfall variability, spectral analysis was conducted for both the complete record (1901–2024) and its three temporal epochs as for All India. The analysis provides insight into the distribution of spectral energy and the stability of oscillatory modes over time.

4.2.1 Complete Period (1901–2024)

The period–amplitude spectrum for the complete Kerala rainfall record is illustrated in Figure 4. A strong spectral peak is observed near **17.71 years**, indicating that decadal to multi-decadal variability constitutes the principal mode of fluctuation in the long-term series. The dominance of this lower-frequency band suggests that Kerala rainfall variability is largely governed by longer-period oscillatory processes within the aggregated signal.

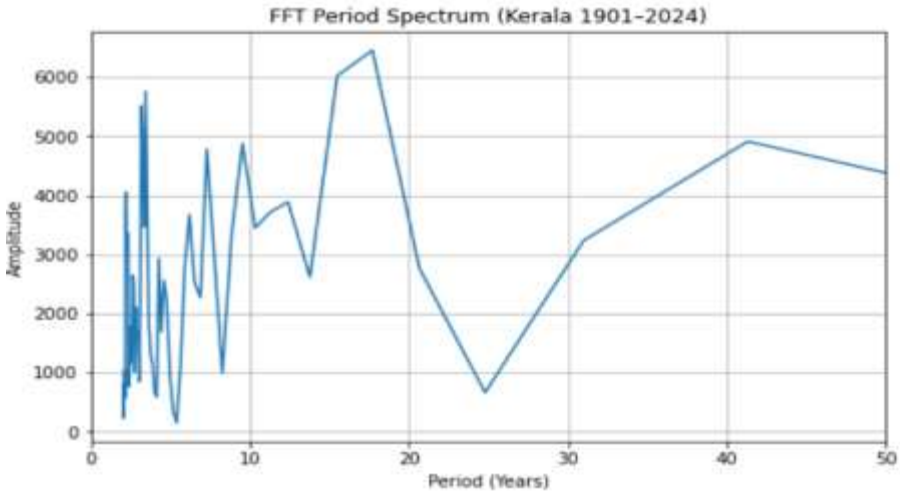
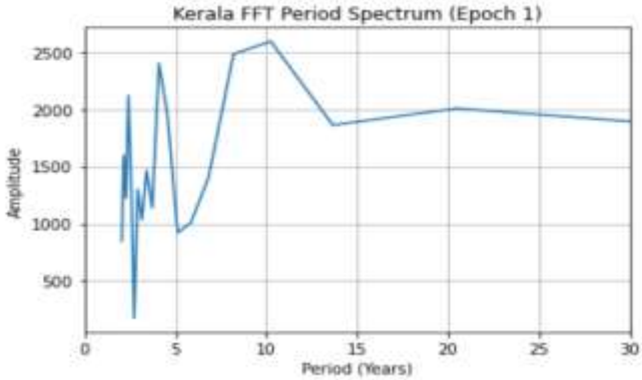
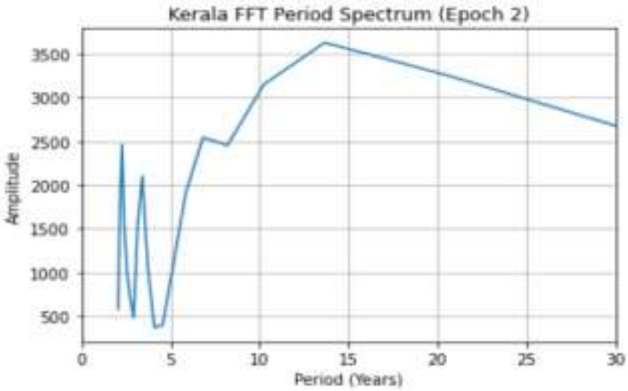


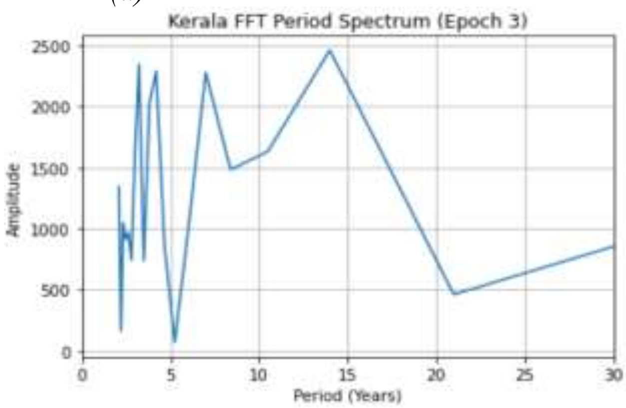
Figure 4. Amplitude spectrum (period vs amplitude) of Kerala annual rainfall (1901–2024)

4.2.2 Epoch-wise Spectral Analysis





(a) *(b)*



(c)

Figure 5. Epoch -wise amplitude spectra of Kerala rainfall: (a) Epoch 1, (b) Epoch 2, (c) Epoch 3.

The epoch-wise spectra for Kerala rainfall are shown in Figure 5. The dominant periodicities for each epoch are (Epoch **1:** ≈ 10.25 years, Epoch **2:** ≈ 13.67 years, Epoch **3:** ≈ 14.00 years). Unlike All-India rainfall, Kerala exhibits persistent dominance within the decadal band across all epochs. Table 2 shows the dominant cycles of Kerala rainfall over the full record and across different epochs. The complete 1901–2024 record highlights a pronounced ~17.7-year dominant cycle with the highest amplitude, reflecting a strong long-term oscillatory component in Kerala rainfall. In contrast, the epoch-wise analysis shows relatively shorter and shifting dominant periods with reduced amplitudes. This demonstrates that the rainfall variability is non-stationary, with evolving periodic scales and a comparatively weaker oscillatory strength in recent decades relative to the full record.

Table 2: Dominant periodicities and corresponding maximum amplitudes of Kerala annual rainfall for the complete period (1901–2024) and individual epochs.

Duration	**Dominant period (Years)**	**Amplitude**
Complete Data: 1901-2024 (124 years)	17.71	6456.0305
Epoch 1: 1901–1941(41 years)	10.250000	2591.929109
Epoch 2: 1942–1982 (41 years)	13.666667	3629.395571
Epoch 3: 1983–2024 (42 years)	14.000000	2462.033599

4.3 Comparative Analysis

A comparative summary of the dominant periodicities for All-India and Kerala rainfall is presented in Table 3. The comparison highlights clear differences in the temporal organization of rainfall variability between the two scales. All-India rainfall shows pronounced shifts in dominant periodicity across epochs, transitioning from interannual variability (≈2–3 years) to longer decadal-scale oscillations. In contrast, Kerala rainfall exhibits relatively stable dominance within the decadal band throughout all epochs. The magnitude of change in dominant periodicity between epochs is therefore greater for the All-India series than for the Kerala series, indicating stronger temporal variability at the national scale. These results suggest that while regional rainfall variability in Kerala maintains a consistent decadal structure, the aggregated All-India rainfall signal reflects more dynamic shifts in its dominant oscillatory modes over time.

These contrasting spectral characteristics highlight the spatial heterogeneity in monsoon rainfall variability, demonstrating that regional rainfall signals may exhibit more stable periodic structures, while the aggregated All-India rainfall index reflects greater temporal modulation of dominant variability modes

Table 3. Comparative evolution of dominant periodicities: All-India vs Kerala

Period	**All-India Dominant Period (Years)**	**All-India Amplitude**	**Kerala Dominant Period (Years)**	**Kerala Amplitude**
1901–2024	2.48 years	1383.9072	17.71	6456.0305
1901–1941	2.411765	768.188780	10.250000	2591.929109
1942–1982	13.666667	796.001431	13.666667	3629.395571
1983–2024	8.400000	554.117117	14.000000	2462.033599

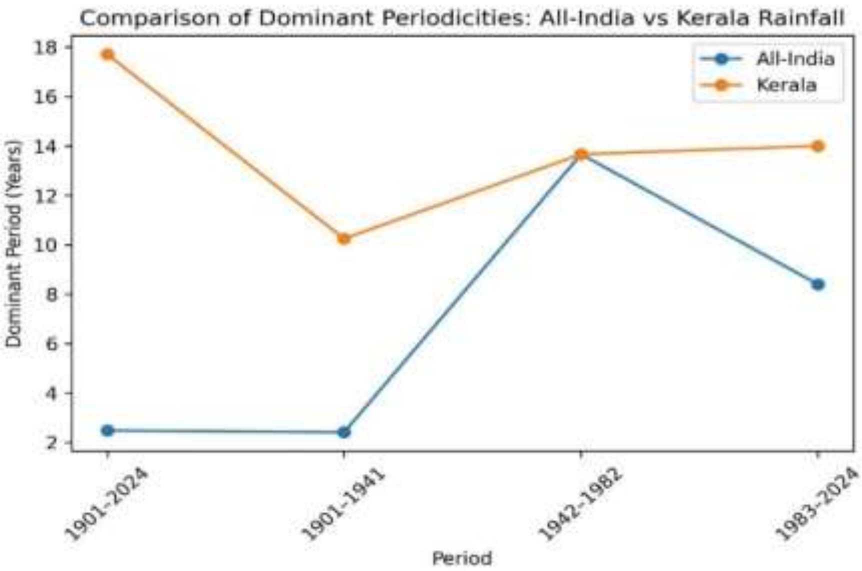


Figure 6:Comparison of dominant periodicities of All-India and Kerala rainfall for the complete period (1901–2024) and the three epochs (1901–1941, 1942–1982, and 1983–2024).

This behavior is visually illustrated in Figure 6, which compares the dominant periodicities for All-India and Kerala rainfall across the complete record and the three epochs. The figure clearly highlights the larger fluctuations in dominant periods for All-India rainfall, while Kerala rainfall remains largely within the decadal range.

Conclusion

This study examined long-term rainfall patterns over India and Kerala during the period 1901–2024 using spectral analysis. The results show that rainfall does not vary randomly but follows certain repeating cycles over time. For the All-India rainfall series, shorter cycles of about 2–3 years dominate the complete record, although the dominant time scale changes across different epochs, indicating that the overall variability structure of the Indian monsoon evolves over time. In contrast, Kerala rainfall shows a stronger and more consistent influence of decadal-scale cycles (around 10–17 years) across all epochs, suggesting relatively stable long-term variability at the regional scale.

Overall, the study successfully identified the dominant periodicities in All-India and Kerala rainfall, examined how these periodicities change over time, and highlighted differences between national and regional rainfall variability. The findings emphasize that rainfall variability contains identifiable temporal patterns that evolve over decades and differ across spatial scales.

Future research could extend this work by exploring the physical climate processes responsible for these periodic cycles. Incorporating large-scale climate drivers such as ocean–atmosphere interactions, teleconnection patterns, and regional circulation systems may help explain the mechanisms behind the observed variability. In addition, applying advanced time–frequency techniques, such as wavelet analysis, could provide deeper insight into how rainfall cycles change continuously over time.

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