# Investigating the Effects of Remal Cyclone on the Rainfall Pattern in Manipur using PERSIANN-Dynamic Infrared Rain Rate near real-time (PDIR-Now) Dataset

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***Abstract***

An investigation is conducted on the hourly and diurnal variation in non-cyclone and cyclone days precipitation patterns in Manipur for the period from 20 to 31 May, 2024. The investigation is based on the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks - Dynamic Infrared Rain Rate near real-time (PDIR-Now) which is a real-time global high resolution (0.04° x 0.04° or = 4km x 4km) satellite precipitation product. The temporal resolutions of daily and hourly data provide detailed insights into rainfall variability. Utilizing a combination of geoprocessing techniques and time-series analysis it has been demonstrated that the cyclonic event in the Bay of Bengal significantly influences the rainfall pattern in Manipur. Time series is decomposed into trend, seasonal and random components for more detailed interpretation of the daily variations in rainfall. The peak rainfall intensity typically occurs between 15:00 hrs and 18:00 hrs local time, based on observed values in the dataset. Conversely, the lowest rainfall intensities are observed during the early morning hours, typically between 03:00 hrs and 05:00 hrs. This general pattern of rainfall is overridden in the cyclonic days during the study period. The findings contribute to a deeper understanding of the use of PERSIANN PDIR-Now dataset for analysing precipitation pattern during extreme weather events, revealing potential applications in disaster management and water management strategies.

**Keywords:** Bay of Bengal, Cyclone, Manipur, PERSIANN-PDIR, Remal.

## Introduction

Tropical cyclones are among the most impactful meteorological phenomena, significantly influencing regional weather, particularly rainfall distribution *(T*ropical Cyclones, n.d., Thanh, et al, 2024).). Such events are especially critical in Northeast India, where unique geographical and climatic features intensify the variability and effects of cyclone-induced rainfall (Zhou and Matyas, 2021). The Remal Cyclone, which has received limited scientific attention, provides an important opportunity to examine these effects in Manipur (Cyclone Remal, North East: Situation Report - 4, 2024). Understanding how this cyclone influences rainfall patterns is essential for improving disaster preparedness and water management strategies. Advances in remote sensing and satellite-based technologies have enabled better monitoring and analysis of precipitation patterns during extreme weather events. Among these tools, the PERSIANN-PDIR-Now dataset has emerged as a highly effective resource for near-real-time rainfall estimation (Hsu et al., 1997). The PERSIANN-PDIR-Now system is based on the PERSIANN algorithm, which uses artificial neural networks to convert infrared satellite imagery into precipitation estimates, but it integrates additional features that enhance its temporal responsiveness and spatial resolution. This dataset includes dynamic infrared data processed with machine learning to generate updated rainfall estimates every 30 minutes, making it particularly suitable for capturing rapidly evolving precipitation events such as tropical cyclones (Nguyen et al., 2018). Furthermore, its high spatial resolution, typically at a 4-km grid, provides detailed insights into local rainfall patterns, which is crucial for regions like Manipur with complex topography (Sorooshian et al., 2021). Compared to other datasets within the PERSIANN family, PERSIANN-PDIR-Now is better suited for analysing cyclonic rainfall events. While the original PERSIANN dataset is highly reliable for long-term rainfall trends and PERSIANN- Cloud Classification System (CCS) performs best in identifying convective systems, both are less effective for real-time monitoring due to slower update cycles (Hong et al., 2004). PERSIANN-PDIR-Now overcomes these limitations, providing the temporal granularity and responsiveness needed to monitor the dynamic precipitation shifts associated with cyclones. According to Gorooh et al. (2022), PDIR-Now demonstrates superior performance in estimating precipitation rates in both types of precipitations involving transition of snow or ice to raindrops as well as in those cases that do not involve this transition in regions with complex terrain, when compared to the PERSIANN-CCS. PDIR-Now also exhibits superior performance to PERSIANN-CCS in near-real-time satellite precipitation estimation (Arellano 2023, Salehi et al. 2022). Its utility in real-time analysis makes it a valuable tool for understanding the spatial and temporal variations of rainfall during extreme weather events, which is critical for disaster preparedness and hydrological modelling. Manipur's distinct landscape, characterised by a combination of hilly terrain and valleys, increases the complexity of analysing changing aspects of rainfall during cyclonic activity. While past studies have explored broader climatological effects of cyclones, there is limited research focusing on the impacts of specific events in this region (Gadgil, 2003). This study aims to fill this gap by utilising PERSIANN-PDIR-Now data to investigate how the Remal cyclone influenced rainfall patterns in Manipur. The outcomes are expected to enhance the understanding of regional hydrometeorological phenomena and support decision-making for disaster risk reduction and water management.

## Study Area

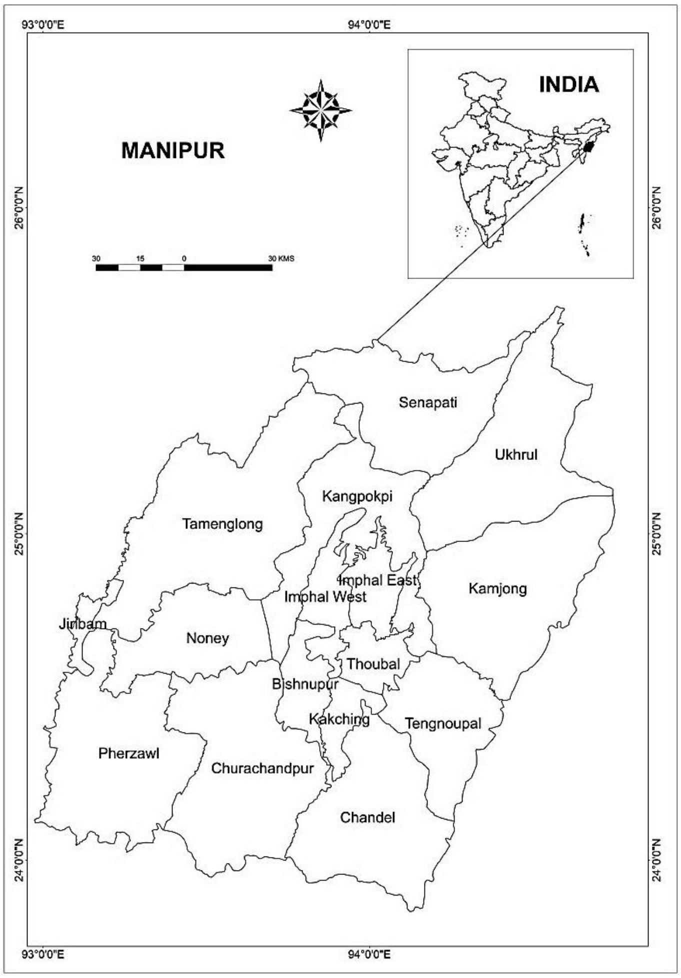


Figure 1: Study Area

Manipur comes under the range of 23.83°N to 25.68°N latitude and 93.03°E to 94.78°E longitude and covers an area of 22,327 sq. km. The state has a central valley region flanked by hills. However, this hill ranges in height between as low as 790 meters to as high as 2,994 meters above sea level. The climatic condition of Manipur is subtropical with average annual rainfall falling within the range of 1,200 mm to 2,000 mm. Its peculiar geographical and climatic conditions make the region highly vulnerable to severe weather events. The residual impacts of cyclones originating from the Bay of Bengal have often plagued the state. Geographically and historically, Manipur is insulated from the direct impacts of the cyclone. Though, the cyclones hit Manipur largely through indirect ways of heavy rainfall and heavy gusts, the impacts occurring within the state are quite damaging. Heavy falls at relentless spells inundate all valley areas of great population and an economically relevant feature. The floods result in very severe obstructions of transport networks, destruct crops, and flood households. Such may precipitate severe socio-economic setbacks in the concerned community. Landslides are more prone when heavy rainfalls occur in the hill regions of Manipur. Landslides destroy structures such as roads and bridges besides causing damage to human life and properties. Heavy winds accompanying cyclonic systems boost the scale of destruction where trees get uprooted, electric power and communication lines are damaged apart from the normal destruction of buildings at a widespread scale. Such interruption can make the crucial service not utilized by the affected communities for a long period. This may indeed worsen the hardship faced through the events. In the long-run, the economy of the state got affected in terms of lowered agricultural productivity, delayed infrastructure development, and stretched disaster management resources. In this regard, Manipur is prone to the indirect effects of cyclones; therefore, a holistic disaster preparedness and mitigation measure should be undertaken to reduce the negative impacts of such events.

## Objectives

The main objectives of the study include examining the variation in rainfall in Manipur during the influence of cyclone Remal that originated in the Bay of Bengal, investigating the intra-day variation in rainfall intensity and highlighting the general pattern of diurnal rainfall.

## Methodology

This study investigates the impact of the Remal Cyclone on the rainfall pattern of Manipur using the PERSIANN-PDIR-Now dataset, a reliable source for near-real-time precipitation monitoring. The datasets of hourly and daily temporal resolutions are used for this study. Daily temporal resolution is used to highlight the variations in the amount of rainfall received during cyclone and non-cyclone days. On the other hand, hourly temporal resolution data is used for examining diurnal variation in rainfall intensity through time-series analysis. The methodology involves four main steps: data collection, cyclone tracking, spatial data processing, and rainfall time-series analysis.

## Data Used and Techniques Employed

The primary dataset used for this study is the PERSIANN-PDIR-Now dataset, which is accessed from the CHRS data portal. This dataset provides high-resolution, near-real-time precipitation estimates derived from infrared satellite data processed with machine learning. The dataset used for the study covers daily and hourly rainfall data at a spatial resolution of 4 km. Thus, the data has both high temporal as well as high spatial resolutions suitable for detailed analysis of rainfall patterns during cyclonic events.

## Cyclone Information

Cyclone information is obtained from the Indian Meteorological Department (IMD). This data includes information on the formation, track, and location of the Remal Cyclone, which is essential for correlating the cyclone’s movement with the rainfall patterns observed in the PERSIANN-PDIR-Now dataset. IMD provides periodic updates regarding the cyclone's development and movement, which are used to identify the timing and geographical extent of significant rainfall events associated with the cyclone.

## Spatial Data Processing in ArcGIS

The PERSIANN-PDIR-Now dataset is provided in geographical co-ordinate system and are required to be converted into a projected co-ordinate system. The rainfall spatial dataset is, therefore, projected into WGS 1984 UTM-zone 46N coordinate system to align with the local geographic extent of the study area, Manipur. Each pixel of the raster data is of

4 km x 4 km dimension in case of PERSIANN PDIR-Now dataset. This means that an area of 4 km x 4 km is represented by a single value of precipitation in millimetres (mm). In other words, the pixel value of daily PERSIANN PDIR-Now dataset represents the total amount of rainfall in mm accumulated during that particular day (00 hours to 23:59 hours) in an area of 4 km x 4 km dimension. It also implies that all the points in the ground within that pixel received an average rainfall amount represented by the pixel value. The pixel is converted into point using raster to points conversion tool in ArcGIS. This transformation allows for the analysis of rainfall data at individual locations across the study area. All the pixels are converted into points in this manner and are interpolated using spline with barriers method to generate the rainfall map for the study of variation in rainfall amounts. This interpolation method is selected to account for the smooth transition of rainfall values between data points while maintaining the integrity of spatial barriers which in the case of the present study is the territorial boundary of Manipur.

**Time Series Analysis**

Time series analysis is conducted on RStudio software. For time series analysis the hourly dataset of precipitation from 20 to 31 May, 2024 is being used. PERSIANN-PDIR-Now dataset of hourly resolution consists of rainfall in millimetres (mm) accumulated during an hour with pixel resolution of 4 km x 4 km dimension. All the points in the ground within a pixel is collectively represented by rainfall value indicated by the pixel value. For the average hourly rainfall value of the state, the mean of all the pixels within the state boundary of Manipur is calculated using zonal statistics tool in ArcGIS. Decomposition of the time-series into trend, seasonal and random component is also performed for deeper interpretation of the underlying pattern of rainfall during the study period. Additionally, box plot is prepared for rainfall in each district for deeper interpretation of the district-wise rainfall pattern during the study period. Box plot statistics are calculated using RStudio for interpretation. Further, rainfall mass curve of hourly temporal resolution is prepared to highlight the hourly accumulation of rainfall throughout the study period reflecting the high intensity points.

**Result and Discussion**

The Indian Meteorological Department (IMD) closely monitored the development and movement of Cyclone Remal from its initial stages over the Bay of Bengal to its eventual dissipation over Northeast Bangladesh. IMD's monitoring process in connection to cyclone Remal began on 21st May 2024, when a cyclonic circulation was detected over the southwest Bay of Bengal, with the formation of a low-pressure area expected by the 22nd May. By 23rd May, this system intensified into a well-marked low-pressure area, moving north-eastwards. On 24th May, the system further developed into a depression, with a defined centre over the central Bay of Bengal. By the 25th May, it had intensified into a deep depression, and the system continued its northward movement, approaching Bangladesh and West Bengal coasts. On 26th May, the depression intensified into cyclonic storm Remal, which later became a severe cyclonic storm (IMD 2024). The storm reached a peak intensity with winds gusting to 110 km/h. On 27th May, Cyclone Remal made landfall between Sagar Islands (West Bengal) and Khepupara (Bangladesh) as a severe cyclonic storm and gradually weakened into a cyclonic storm and then into a deep depression over the following days. By 28th May, the storm weakened further, transitioning into a depression over Bangladesh, before dissipating completely by 29th May as an upper-air cyclonic circulation. The IMD's detailed tracking and reporting provided critical information of the cyclone Remal required for this study.

### Rainfall Pattern from Daily Temporal Resolution Dataset

The raster dataset of daily PERSIANN PDIR-Now has pixel size of 4 km x 4 km dimension. The pixel values represent the amount of rainfall in millimetres accumulated during a day (from 00:00 Hours to 23:59 hours) in an area of 4 km x 4 km dimension. The mean of rainfall of a district determined through zonal statistics, therefore, represents the mean of all the pixels within that district. The rainfall data of Manipur from 20 May to 31 May, 2024 is prepared in this manner. The analysis of rainfall data for Manipur from 20 May to 31 May, 2024, provides compelling evidence of the significant influence exerted by cyclone Remal on the region's precipitation patterns. The cyclone, which intensified on 26 May and dissipated on 29 May, caused widespread and substantial rainfall across Manipur, a state located approximately 500 to 600 km from the Bay of Bengal. The rainfall data, visualised on the spatial map (Fig. No. 2), reveals distinct geographical disparities in the distribution and intensity of precipitation, highlighting the role of the cyclone's moisture-laden winds and the state's varied topography. Jiribam, situated on the western side of Manipur near the Cachar plains of Assam, emerges as the district most impacted by the cyclone. As depicted in the map (Fig. No.2) Jiribam recorded the highest rainfall, with a remarkable 58 mm on 26 May. Tamenglong, a northern hill district characterised by its elevated terrain and dense forests, is another area prominently affected, as reflected in the map (Fig. No.2). The district experienced substantial rainfall peaks, recording 35.58 mm on 26 May. Amongst the southern hill districts, Churachandpur witnessed notable rainfall, with its highest daily total of 35.41 mm recorded on 26 May. Noney, situated in the central hills of Manipur, also experienced significant rainfall during this period recording a total of 41.51 mm on 26 May, marking one of the highest totals during the cyclone's peak activity. In the central plains, Imphal West and Imphal East, which encompass the state capital and surrounding areas, observed moderate yet persistent rainfall during the cyclone's influence. The northeastern hill districts of Senapati and Ukhrul experienced steady rainfall, though their totals were comparatively lower. The results (Fig. No. 2) thus, emphasise the widespread impact of cyclone Remal across Manipur, with the western and southern districts of Jiribam, Tamenglong, and Churachandpur identified as the most affected. The influence of the cyclone diminishes towards the central plains and northeastern hills, demonstrating the interplay between cyclonic activity, topography, and rainfall distribution. Such mapped data is invaluable for understanding regional vulnerabilities and guiding future disaster preparedness and response efforts.

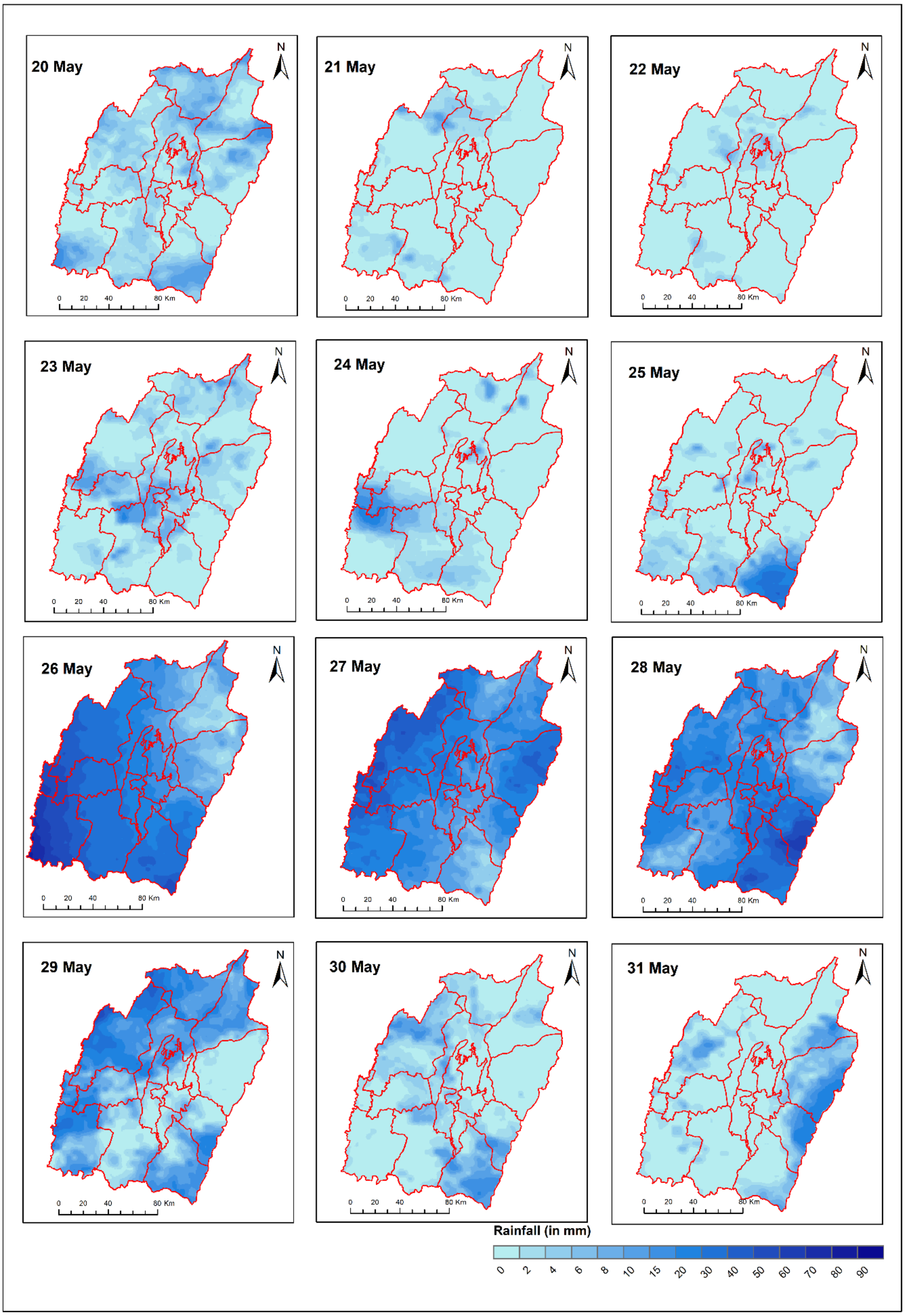


Fig. No. 2. Pre-cyclonic, Cyclonic and Post-Cyclonic Rainfall in Manipur

Using box-plot and its related statistics a deeper investigation of the spatial variability of rainfall during the study period is conducted. The analysis reveals substantial spatial variability in rainfall distribution, as indicated by the descriptive statistics. The district of Jiribam recorded the highest value of maximum rainfall of 58 mm, with a mean of 14.26 mm and a standard deviation (SD) of 19.12 mm during the study period, reflecting high variability in rainfall patterns (Fig. No. 3). The interquartile range (IQR) of 17.16 mm further supports this observation, and a significant outlier of 58 mm indicates occasional heavy rainfall events that deviate considerably from the general distribution. On the other hand, Ukhrul, which had a mean rainfall of 5.34 mm, a maximum of 17.16 mm, and an SD of 5.31 mm, exhibited more stable and lower rainfall compared to other districts. Its IQR of 5.81 mm underscores this consistency, with no extreme outliers recorded (Fig. No. 3).

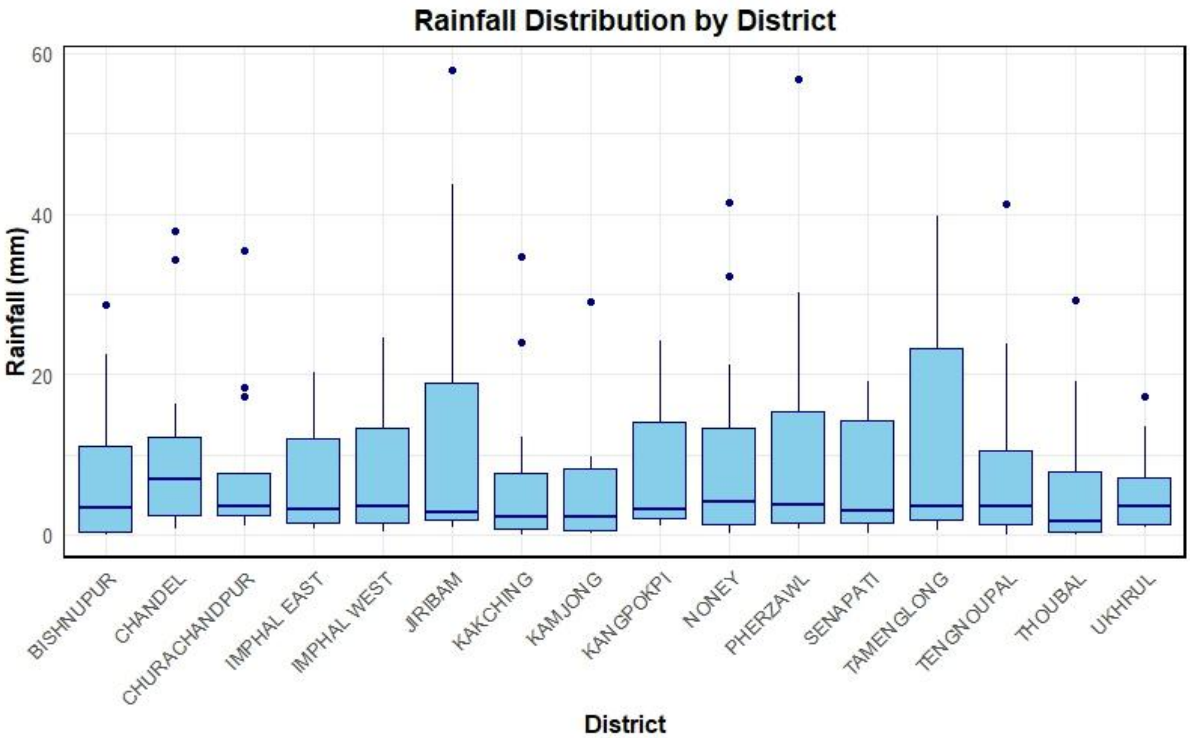


Fig. No. 3. District-wise rainfall variation (20-31 May, 2024)

Districts such as Tamenglong and Pherzawl also depicted a wide variability in rainfall. Tamenglong had the highest value of 39.82 mm and mean of 11.97 mm along with an SD of 14.53 mm (Fig. No. 3). The district also depicted a wide IQR of 21.38 mm indicating a wide range in the distribution of rainfall. As alike, Pherzawl experienced one of the highest maxima of amount of rainfall and a relatively raised mean of 11.57 mm with a high standard deviation of 16.80 mm. As there is extreme outlier at a value of 56.85 mm, the instances of intense rain at times would be more significant in this district. Both these districts have, therefore, important variability in relation to significant variation in rainfall occurrences, which affects agricultural and also water resource activities. In districts Chandel, Churachandpur, and Noney, the mean rainfall range was between 8.01 mm and 10.96 mm, with the highest value recorded in Chandel. Maximum rainfall, which was reported at Chandel was 37.82 mm and its outlying values emerged at 34.29 and 37.82 mm with some isolated heavy intensity bursts during the period of observation. Churachandpur had high variability, and it also showed the maximum of 35.41 mm along with an SD of 10.46 mm; the same area also reported many outliers with values at 17.30 mm, 18.39 mm, and 35.41 mm. The variability for Noney is also very similar, as the maximum rainfall has been 41.51 mm with an SD of 13.76 mm along with an outlier at 41.51 mm and 32.22 mm. These districts show a trend of moderately high mean rainfall with significant variability. Districts in the central plain, such as Imphal East, Imphal West, and Thoubal, showed lower mean rainfall values of 6.86 mm, 8.32 mm, and 6.40 mm, respectively. The rainfall in these districts was less variable, as indicated by narrower IQRs, 10.56 mm for Imphal East, 11.74 mm for Imphal West, and 7.55 mm for Thoubal. The maximum values of rainfall in these districts ranged between 20.21 mm and 29.29 mm with no extreme outliers. Thus, it was inferred that the pattern of rainfall is more stable and predictable as compared to the districts having higher maxima and outliers. Amongst the other districts, Kakching showed a moderate variation in the range of 7.26 mm with a maximum value of 34.58 mm but including two outliers: 24.05 mm and 34.58 mm indicating sometimes heavy rain. The mean values in Senapati and Kangpokpi were at 7.11 mm and 7.91 mm, respectively, indicating maxima to be at 19.10 mm and 24.23 mm with no significant outliers, indicating fairly constant rainfall pattern. Tengnoupal and Kamjong showed moderate mean rainfall at 8.97 mm and 5.62 mm, respectively, with higher variability in Tengnoupal, as reflected by its maximum of 41.29 mm and SD of 12.41 mm. The districts that had the lowest variability in terms of rainfall were Bishnupur, with a mean of 7.63 mm and a maximum of 28.68 mm, and Kamjong, with a mean of 5.62 mm and a maximum of 29.11 mm. Both had relatively stable rainfall distributions, given their narrower IQRs, which were at 10.56 mm and 7.68 mm, respectively. The number of outliers was fewer or absent, hence further emphasizing the consistency of the rainfall in those regions. The findings depict an extensive spatial variability of rainfall over the region, indicating more variability in districts located towards the western, northern, and southern directions with districts such as Jiribam, Tamenglong, and Pherzawl as opposed to those northeastern districts such as Ukhrul and Kamjong where variability and extremes of rainfall events are much lesser and more stable. Several districts have outliers, which reflect extreme rainfall events that may be problematic for agricultural planning, water resource management, and disaster preparedness. The study findings point toward region-specific interventions to mitigate the impacts of rainfall variability in the state.

**Time series analysis**

The analysis of hourly rainfall data from May 20 to May 31, 2024, for Manipur, a state located relatively farther away from the Bay of Bengal in northeastern India, provides understandings into the diurnal and temporal variations in precipitation and the extended influence of cyclone Remal on rainfall patterns. Despite the state's considerable distance from the Bay of Bengal, the findings illustrate the significant atmospheric impacts of the cyclone, which strengthened from May 26 and dissipated by May 29, 2024. The time-series plot of the observed hourly rainfall reveals significant insights into its temporal variability during the study period. The hourly mean rainfall during the study period averages 0.42 mm, with a standard deviation of 0.78 mm (Fig. No. 4). These values indicate a considerable fluctuation in rainfall intensity across different hours. Notably, the maximum observed rainfall reaches 5.67 mm in an hour, highlighting isolated events of heavy precipitation. Conversely, there are periods with no rainfall, as indicated by the minimum observed value of 0 mm/hr. The presence of such extreme values suggests episodic rainfall, characteristic of pre-monsoon or early monsoon weather patterns in the region. A closer examination of the observed component (Fig. No. 4) reveals significant variability between dates, particularly during the period influenced by cyclone Remal. From 26 to 29 May 2024, the observed rainfall patterns show pronounced increases corresponding to the strengthening and eventual dissipation of cyclone Remal. On 26 May 2024, the highest mean hourly rainfall of 1.17 mm was recorded, with a peak hourly rainfall of 5.67 mm (Fig. No. 4). The rainfall remained elevated on 27 May 2024, with a mean of 1.07 mm and a maximum of 3.24 mm/hr. These heightened values reflect the cyclone's impact as it intensified, leading to sustained heavy precipitation in the region. By 28 May 2024, the mean rainfall was slightly lower at 1.05 mm/hr, although localized heavy rainfall events persisted, with a maximum of 3.45 mm/hr (Fig. No. 4). The dissipation of the cyclone on 29 May 2024 coincided with a marked decline in rainfall, as the mean hourly value dropped to 0.57 mm, and the maximum rainfall recorded was 1.60 mm (Fig. No. 4). These observations highlight the direct influence of Remal on the rainfall dynamics, with its lifecycle leaving a clear imprint on the observed component (Fig. No. 4) of the time series.

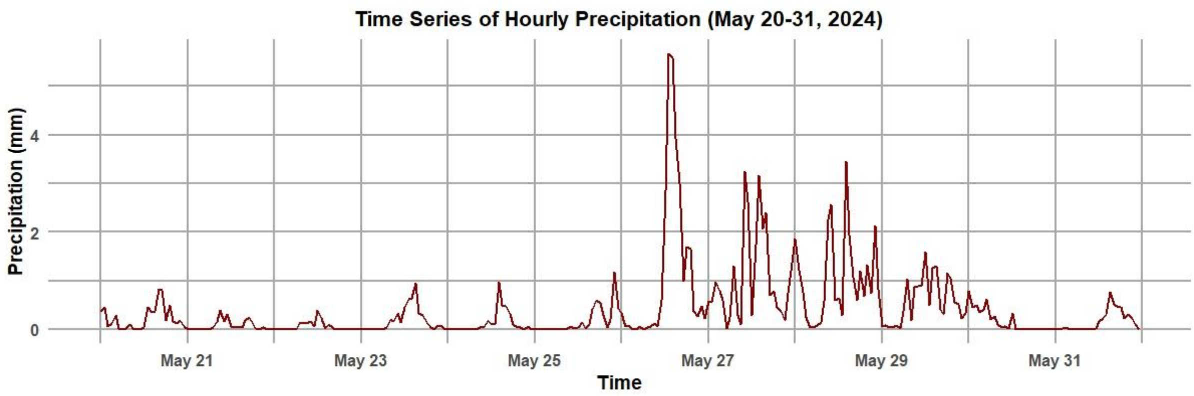


Fig. No. 4. Precipitation in Manipur during the study period

## Rainfall Mass Curve

The rainfall mass curve of the study period for Manipur identified two instances of high-intensity rainfall exceeding 5.5 mm per hour (mm/hr), occurring consecutively on May 26, 2024, during the early afternoon hours (Fig. No. 5). At 13:00 hrs, a significant precipitation of 5.67 mm/hr was recorded, marking the commencement of high-intensity rainfall. This was followed by another substantial downpour at 14:00 hrs, with precipitation slightly reduced to 5.59 mm/hr. Subsequently, by 15:00 hrs, rainfall intensity decreased but remained high, measuring 3.93 mm/hr. At 16:00 hrs, the intensity further declined but remained above 3 mm/hr, with a recorded value of 3.01 mm/hr (Fig. No. 5).

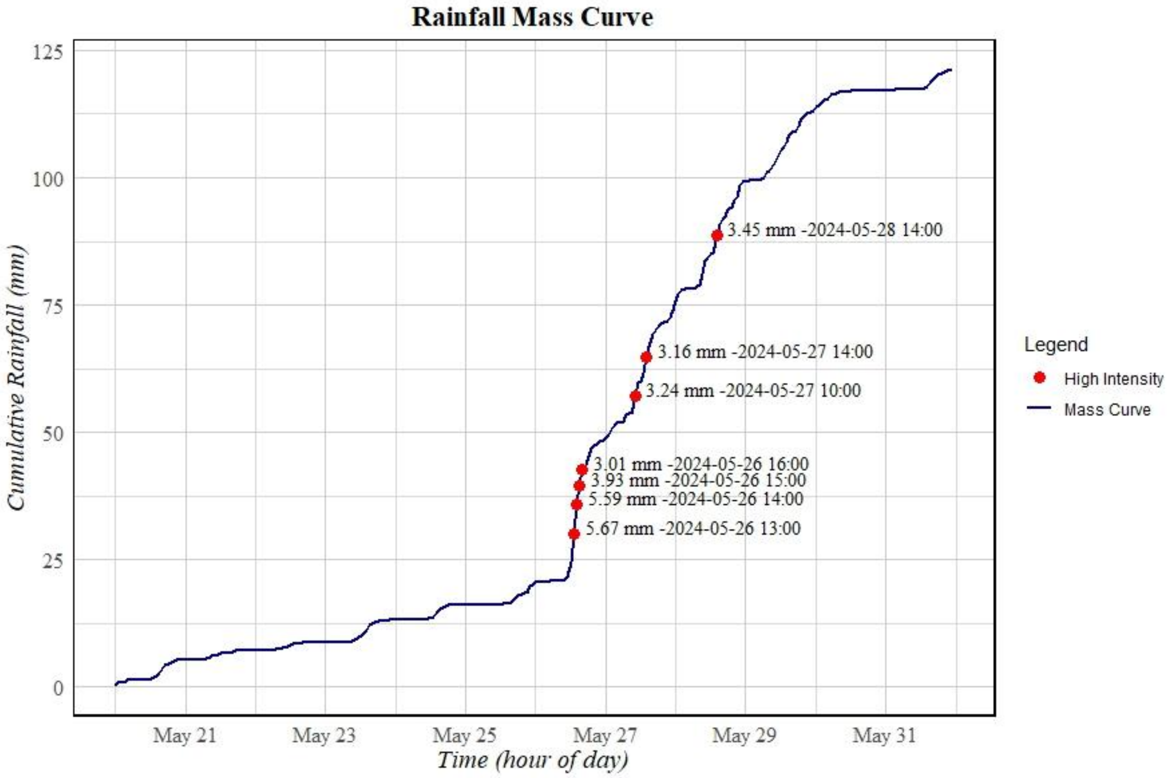


Fig. No.5. High Intensity Points

Such patterns of high-intensity rainfall are critical for assessing hydrological impacts, as they play a significant role in influencing flood risks and water resource management. On May 27, 2024, two rainfall events exceeding 3 mm/hr were observed. At 10:00 hrs, precipitation was recorded at 3.24 mm/hr, followed by another event at 14:00 hrs, measuring 3.16 mm/hr (Fig. No. 5). Finally, on May 28, 2024, at 14:00 hrs, a precipitation value of 3.45 mm/hr was observed. These data points provide valuable insights into rainfall intensity and distribution, contributing to a better understanding of regional hydrological dynamics. These instances represent sustained periods of moderate to high rainfall intensity, which could influence soil saturation levels, surface runoff, and potential localized flooding.

**Time-series decomposition**

The time series decomposition of hourly mean rainfall in Manipur, India, from 20 May to 31 May 2024 reveals intricate patterns and variations across observed, trend, seasonal, and random components. The following discussion elaborates on the characteristics and implications of these findings. A distinct diurnal cycle of rainfall was observed throughout the study period. Under typical conditions, night-time precipitation, particularly from 00:00 to 06:00 hrs, was minimal or absent. Daytime rainfall, particularly between 12:00 and 18:00 hrs, consistently exhibited higher intensities, with significant peaks during the cyclone's active phase. Typically, late afternoon and evening hours saw a decline in precipitation intensity. However, this trend was disrupted during the cyclone's influence. Sustained rainfall extended into the late evening hours during May 26 and May 27, with totals exceeding 1 mm/hr even during hours that usually exhibit a decline. Periods of low rainfall, particularly in the early morning and late evening, were dominant in the absence of significant synoptic disturbances. However, the influence of cyclone Remal led to deviations from this pattern, notably increasing night-time precipitation. These findings highlight the interconnectedness of regional weather systems and the significant reach of cyclonic disturbances. Despite being located relatively farther away from the Bay of Bengal, Manipur experienced notable rainfall enhancements due to cyclone Remal. This highlights the capacity of such systems to modulate precipitation patterns over vast areas.

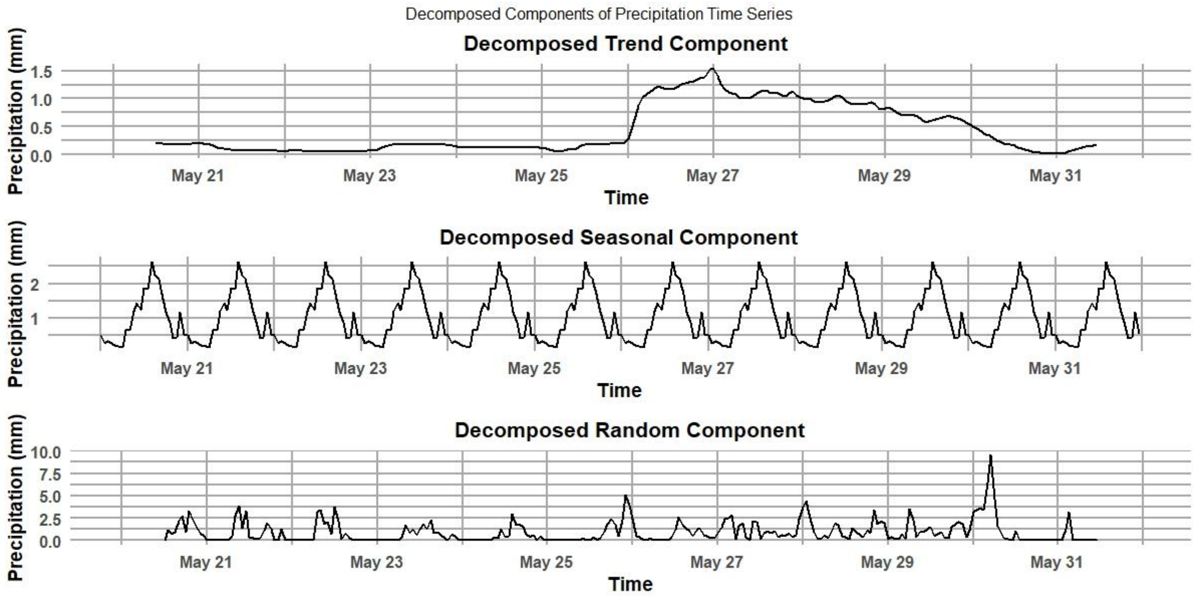


Fig. No. 6. Rainfall Pattern in Manipur

## Trend Component

The trend component, which reflects the underlying baseline rainfall over the study period, shows a mean value of 0.44 mm/hr (Fig. No. 6). Its variability, as indicated by a standard deviation of 0.44 mm/hr, suggests gradual shifts in baseline rainfall levels, likely influenced by broader climatic factors. The trend ranges from a minimum of 0.013 mm/hr to a maximum of 1.54 mm/hr (Fig. No. 6). These values indicate that while the baseline rainfall remains generally low, there are periods of slight increases that might correspond to the onset of monsoon circulation or other large-scale meteorological phenomena. The influence of cyclone Remal on the trend component is particularly noteworthy. On 26 May 2024, the trend component reached an hourly mean of 1.14 mm, marking one of the highest baseline levels during the study period (Fig. No. 6). This elevated trend persisted on 27 May 2024, with a mean of 1.12 mm/hr, and began to decline on 28 May 2024, registering at 0.95 mm. By 29 May 2024, the trend had decreased further to 0.68 mm/hr, indicating the waning influence of the cyclone (Fig. No. 6). These variations highlight the cyclone's capacity to elevate the baseline rainfall significantly, contributing to sustained wet conditions even beyond the immediate heavy rainfall events. Within a single day, the trend component exhibits noticeable intra-day fluctuations, often mirroring the gradual build-up or decline of weather systems. For example, during the cyclone’s peak on 26 May 2024, the trend component starts with moderate values in the early hours, steadily increases through midday as the cyclone strengthens, and begins to plateau or decline slightly by late evening. This pattern reflects the evolving nature of atmospheric processes and their impact on baseline rainfall levels throughout the day. Similar intra-day variations can be observed during other periods of heightened activity, emphasizing the dynamic interplay between large-scale meteorological phenomena and localized baseline rainfall trends.

## Seasonal Component and Diurnal Patterns

Seasonality plays a significant role in the time series, as evidenced by the seasonal component's mean value of 1.00 mm/hr and a standard deviation of 0.73 mm/hr (Fig. No. 6). The cyclical nature of rainfall is apparent from the seasonal values ranging between 0.15 mm/hr and 2.63 mm/hr. These oscillations indicate predictable patterns in rainfall intensity, possibly governed by diurnal heating, local convection processes, and atmospheric moisture availability. Peak seasonal values align with expected periods of enhanced convective activity, while lower seasonal values suggest transitional phases or times of reduced atmospheric instability. A pronounced diurnal variation is evident in the observed rainfall, with a clear peak occurring during the late afternoon to early evening hours. Specifically, the peak rainfall intensity typically occurs between 15:00 hrs and 18:00 hrs local time, based on observed values in the dataset (Fig. No. 6). This period aligns with the culmination of diurnal heating, which promotes convection and localized thunderstorm activity. Conversely, the lowest rainfall intensities are observed during the early morning hours, typically between 03:00 hrs and 05:00 hrs (Fig. No. 6), when atmospheric instability is minimal. The influence of cyclone Remal on diurnal patterns is particularly striking. During the cyclone's peak on 26 May 2024, the usual diurnal peak between 15:00 hrs and 18:00 hrs is amplified, with rainfall intensities exceeding 5 mm/hr in isolated hourly observations (Fig. No. 6). This enhancement is attributed to the cyclone's ability to sustain convective activity throughout the day, overriding typical diurnal fluctuations. Similarly, during the cyclone's weakening phase on 28 May 2024, the diurnal peak remains evident but with reduced intensity, reflecting the gradual normalization of atmospheric conditions.

## Random Component

The random component exhibits the highest variability among all decomposed elements, with a mean of 0.93 mm/hr and a standard deviation of 1.25 mm/hr (Fig. No. 6). The range of this component extends from 0 to 9.55 mm/hr, underscoring the presence of irregularities and anomalies in hourly rainfall. Such deviations from the expected trend and seasonal patterns may arise from localized weather systems, including thunderstorms, squalls, orographic effects, or unanticipated shifts in moisture dynamics. The extreme values in this component highlight the unpredictable nature of rainfall, particularly in a region shaped by complex topography and varied climatic influences.

## Conclusion

This study provides a comprehensive analysis of cyclone Remal’s impact on rainfall patterns in Manipur, highlighting the complex spatial and temporal dynamics of cyclone-induced precipitation in the region. The significant spatial variability in rainfall intensity observed across different districts reflects the influence of Manipur's diverse topography on the cyclone's effects. Temporal analysis further revealed disruptions to the diurnal and seasonal rainfall patterns, with elevated nighttime precipitation and extended seasonal peaks during the cyclone's active phase. These findings demonstrate the cyclone's capacity to generate localized and intense precipitation events, as evidenced by the peak hourly rainfall recorded on May 26, 2024. The use of high-resolution satellite data such as PERSIANN-PDIR-Now dataset, spatial analysis, and temporal modelling proved essential in capturing the variability in rainfall patterns, demonstrating the value of advanced tools in studying complex meteorological phenomena. The research enhances our understanding of cyclone-induced rainfall in northeastern India and offers practical implications for disaster management, agricultural planning, and water resource management. By addressing the observed variability and its implications for risk assessment, this work emphasizes the importance of strengthening resilience in regions vulnerable to extreme weather events. The findings contribute to a growing body of knowledge that supports the development of climate adaptation strategies to mitigate the impacts of increasingly frequent and severe cyclones.

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