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*Research Article*

# DIURNAL CYCLE OF PRECIPITATION AND EXTREMES IN NEPAL

***Binod Dawadi[1,2,*], Dipendra Lamichhane[3,4], Darwin Rana[1], Anuja Bohara[1], Chitra Bahadur Shrestha[1], Shrijana Giri[1]***

[1]*Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu 44613, Nepal*
[2]*Kathmandu Center for Research and Education, Chinese Academy of Sciences-Tribhuvan University, Kathmandu 44613, Nepal*
[3]*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
[4]*University of Chinese Academy of Sciences, Beijing 100049, China*
**Correspondence: binod.dawadi@cdhm.tu.edu.np*

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## ABSTRACT
This study examines the spatio-temporal distribution of hourly precipitation across Nepal using Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (IMERG) data from 2015 to 2021. The findings indicate that hourly precipitation intensity during the monsoon season can reach up to 0.7 mm/hr, while pre-monsoon intensities peak at 0.2 mm/hr. These intensities are predominantly concentrated in mid- and low-elevation areas of central and eastern Nepal. Post-monsoon and winter seasons exhibit high-intensity precipitation patches over high-elevation regions in the western, central, and eastern peripheries of the country. The annual distribution of hourly precipitation shows a pronounced peak during the monsoon season, indicating that a significant portion of the total annual precipitation occurs during this period. Extreme precipitation events follow a similar seasonal distribution, with monsoon extremes exceeding 15 mm/hr. The diurnal cycle of monsoonal precipitation shows unique characteristics, peaking at 0.65 mm/hr around midnight and decreasing to 0.2 mm/hr by late morning, then increasing steadily in the afternoon and evening. Additionally, the study contrasts hourly heavy precipitation extremes (≥10 mm/hr or day) with daily extremes, noting that hourly extremes, despite being accumulated into daily measures, present a higher frequency, and pose greater short-term hazard risks. This analysis over a seven-year period suggests the need for continued research to determine spatial and temporal trends in hourly versus daily extreme precipitation patterns, particularly in the context of climate change and its impacts on regional hydrology and meteorology.

**Keywords:** Extreme precipitation events, hourly precipitation, IMERG, monsoon, spatio-temporal distribution

## INTRODUCTION
Precipitation plays a fundamental role in the hydrologic cycle and serves as a key indicator in climate change studies (Anders *et al.*, 2006; Held & Soden, 2006). Its variability and distribution are critical for understanding regional and local water supply dynamics. In recent years, the analysis of long-term precipitation trends and their impacts has garnered significant attention, particularly in the context of climate change (Dalagnol *et al.*, 2022; Wasti *et al.*, 2022). The progression of global warming enhances the atmosphere's capacity to retain moisture and can increase the frequency and intensity of extreme precipitation events globally (Alexander *et al.*, 2006; Sharma *et al.*, 2023; Utsumi *et al.*, 2011). These events, characterized by unusually high rainfall over short periods, have been observed to occur more frequently, leading to natural disasters in different climatic regions, ultimately bringing severe challenges to agricultural production and socioeconomic systems. Thus, understanding the mechanisms and patterns of extreme precipitation events is essential for improving predictive models, and developing effective adaptation and policy strategies to enhance resilience and sustainability.

Precipitation monitoring stations in Nepal are limited and sparsely distributed, because of varied and complex topography. These observations primarily provide data on a daily basis, with only recent periods having access to hourly data. Previous studies on precipitation and its extremes in Nepal (e.g., Hamal *et al.* (2020a), Hamal *et al.* (2021b), Sharma *et al.* (2020a), Shrestha *et al.* (2021), Talchabhadel *et al.* (2018), Talchabhadel *et al.* (2021a), Talchabhadel *et al.* (2021b)) mostly relied on daily or monthly datasets. However, changes in precipitation are largely determined by changes in frequency or intensity, which are directly linked to the time resolution of precipitation records (Almazroui *et al.*, 2021; Huang *et al.*, 2017). For instance, for the same daily precipitation amount, the distribution of precipitation over longer or shorter durations can vary significantly in intensity. Therefore, findings based on daily precipitation data cannot be directly extrapolated to hourly resolutions (Trenberth *et al.*, 2003). In some instances, heavy hourly precipitation might be misclassified as normal precipitation, when only daily data is considered. This limitation significantly hinders a comprehensive understanding of short-term (sub-daily) extreme precipitation events.

Despite this limitation, Nepal has experienced several extreme episodes, such as flash floods and landslides, triggered by intense precipitation (Fig. 1). These events have resulted in substantial human and infrastructure loss across the country. Relying solely on daily data may also restrict our understanding of the nature and frequency of such extremes as it fails to capture short-term variations (Shrestha & Deshar, 2014). In addition, Nepal's topography and climatic conditions make it particularly vulnerable to these extreme events. Some previous studies have indicated a high probability of future enhancement in high-intensity precipitation extremes in the mountainous region (Sharma *et al.*, 2021a). Therefore, there is an urgent need to characterize the spatio-temporal distribution of sub-daily extreme precipitation events to accurately assess the risks and develop effective mitigation strategies for the protection of vulnerable communities and infrastructure.

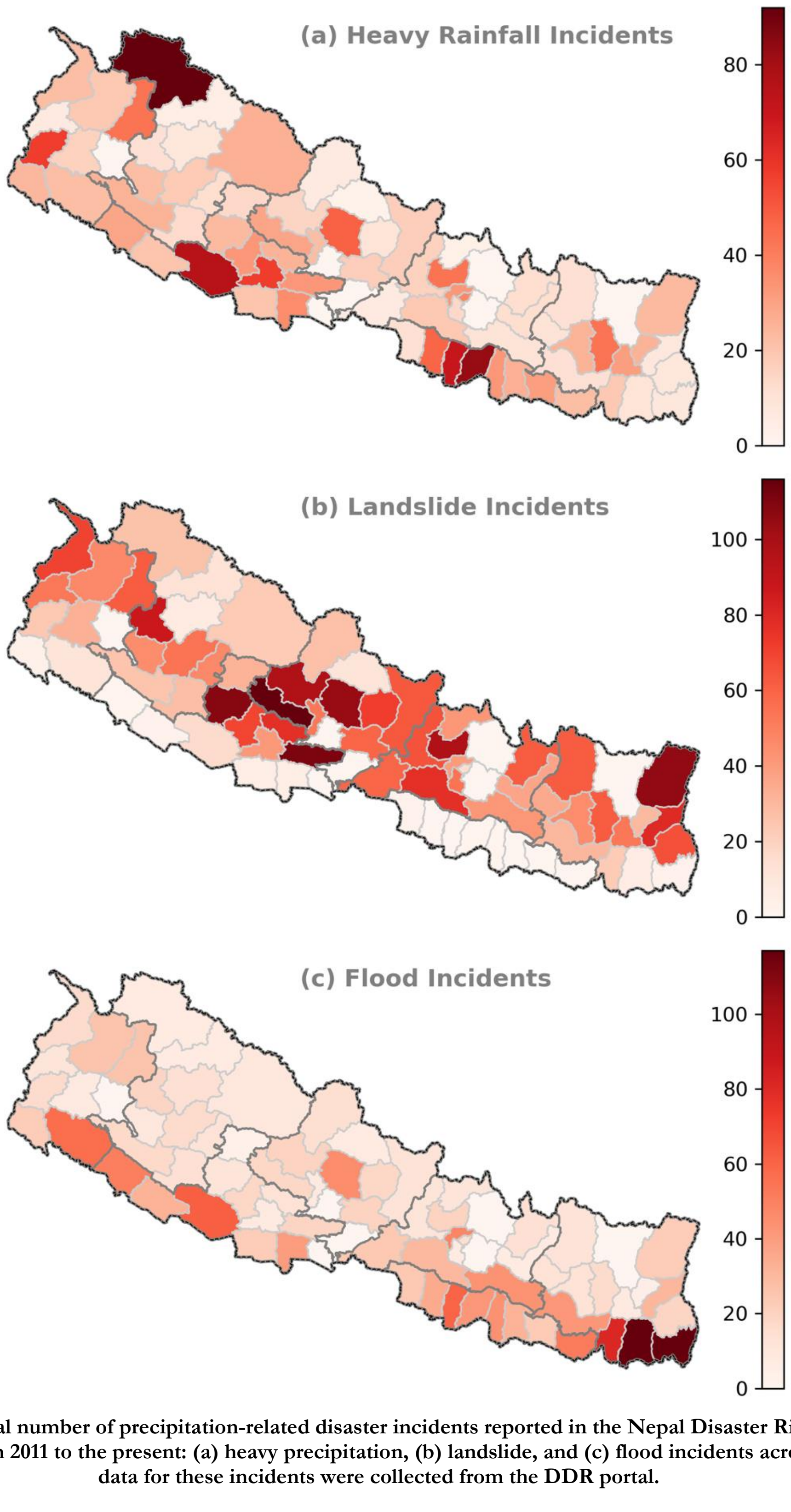


**Figure 1. The total number of precipitation-related disaster incidents reported in the Nepal Disaster Risk Reduction Portal (DDR) from 2011 to the present: (a) heavy precipitation, (b) landslide, and (c) flood incidents across Nepal. The data for these incidents were collected from the DDR portal.**

Several previous studies have employed various datasets, including alternative satellite precipitation products, to investigate precipitation and its extreme characteristics in Nepal. For example, Talchabhadel *et al.* (2018) and Karki *et al.* (2017) examined the distribution of daily extreme precipitation using observational data, while Sharma *et al.* (2020c), Nepal *et al.* (2021) and Shrestha *et al.* (2021) utilized gridded precipitation products. These studies have shed light on new aspects of extremes in Nepal, such as the increasing trend of precipitation extremes over time and the identification of extreme hotspots in the mid-hill areas. However, it remains unclear whether the changes in total or extreme precipitation amounts at hourly and daily time resolutions are driven by the same dominant factors, such as changes in frequency or intensity, especially in the context of Nepal.

Furthermore, most of these studies have primarily focused on daily timescales, neglecting the exploration of the diurnal precipitation cycle and short-term extreme characteristics largely in this region. To address this knowledge gap, our study aims to enhance the understanding of sub-daily precipitation patterns and their characteristics using global high-resolution gridded products. This approach will provide more precise insights into the precipitation dynamics at high-temporal resolution in Nepal, which is crucial for the development of effective water resource management and disaster mitigation strategies.

## MATERIAL AND METHODS

### Study Region and Datasets

Nepal, situated between China and India in South Asia, exhibits a diverse range of climates due to its varied topography, which encompasses lowland plains, mid-hills, and the towering peaks of the Himalayas. The country's climate transitions from subtropical in the southern plains to alpine in the high mountainous regions. Nepal experiences a monsoon-dominated climate, with the majority of its annual precipitation occurring between June and September (Kansakar *et al.*, 2004; Khadka *et al.*, 2023; Sharma *et al.*, 2020b). This seasonal variability, coupled with the complex geography of the region (Dawadi, 2017; Dawadi *et al.*, 2020; Pokharel *et al.*, 2019), makes Nepal highly susceptible to extreme weather events, including intense precipitation, flash floods, and landslides. High-elevation areas in Nepal are particularly complex and steep, thus, precipitation in these regions can trigger massive flooding in the downstream areas, exacerbating the impact of extreme weather events. These incidents frequently result in significant loss of human life, damage to property, and various other disruptions, particularly during the monsoon season. The Disaster Risk Reduction (DRR) portal reports numerous such incidents each year (Fig. 1), underscoring the persistent vulnerability of Nepal to these natural hazards.

For this study, we utilized the Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG) data from 2015 to 2021, which provides high-resolution precipitation estimates on a half-hourly basis (Huffman *et al.*, 2019). IMERG combines information from multiple satellite sensors to produce gridded precipitation data with a spatial resolution of 0.1 degrees (approximately 10 kilometers) and a temporal resolution of 30-min. It covers the region from 60° N to 60° S and is available from 2000 onwards (Huffman *et al.*, 2015). Compared to daily observation data, this dataset is able to capture short-term precipitation variations and extreme events more effectively than other satellite products in Nepal (Sharma *et al.*, 2020d; Nepal *et al.*, 2021). The previous study has already shown that IMERG data provides the best alternatives for gauge observation in Nepal (Sharma *et al.*, 2020d). Moreover, Talchabhadel *et al.* (2022) have shown that these data can capture the precipitation at a sub-daily scale and can be applied for near-real-time exploration of extreme events. By employing the IMERG datasets, our study aims to investigate the sub-daily precipitation characteristics in Nepal. The insights gained from this research will be valuable for improving predictive models and developing effective strategies for mitigating the impacts of extreme precipitation events.

### Method

For the analysis, we initially collected half-hourly IMERG data and then aggregated it into hourly, seasonal, and annual timescales. As the IMERG dataset provides precipitation data in UTC, we converted it to Nepali local time (+5:45). This enabled us to align the data with the local time zone for a more accurate analysis. To investigate the daily precipitation cycle, we calculated the average precipitation for each hour of the day for each year. This allowed us to examine the variations in precipitation throughout the day. Additionally, we computed the total precipitation for each hour to identify areas with peak precipitation distribution. To analyze the precipitation patterns further, we determined the total number of wet hours over a specific time span and identified the number of hours with precipitation exceeding the 99th percentile of the wet hour distribution. This analysis helped us understand occurrence of the extreme precipitation events on an hourly basis across the country. Given that the majority of precipitation (80% of total annual precipitation) occurs during the monsoon season (June to September), our analysis primarily focused on this season. We used the R10mm ("heavy precipitation extreme") index, which quantifies the number of hours or days with significant precipitation within a particular period. In high-elevation areas, precipitation during the winter season predominantly occurs as snow, unlike in low-elevation areas where it is mainly rain. The IMERG datasets used in our study do not differentiate between snow and rain, leading us to refer to all forms of precipitation as "precipitation" throughout the manuscript.

In this study, we utilized IMERG data from 2015 to 2021. Although IMERG data has been available since 2000, the processing of sub-hourly data requires significant computational resources. Due to limited computational capacity, our analysis is confined to this specific period. Nevertheless, our study is the first to utilize high-resolution IMERG data to examine sub-daily precipitation patterns in Nepal. The selected timeframe allows for a robust analysis of recent precipitation patterns and extreme events, providing critical insights into the dynamic climate of the region. This research work paves the foundation for future studies by offering an understanding of sub-daily precipitation characteristics, which will be valuable for improving water resource management and disaster mitigation strategies in Nepal.

## RESULTS AND DISCUSSION

### Spatial distribution of hourly precipitation intensity

To provide a comprehensive understanding of precipitation patterns, Fig. 2 presents the average hourly precipitation intensity for different seasons and on an annual timescale. The spatial distribution of precipitation in Nepal exhibits significant seasonal variability, with 80 % of total precipitation occurring during the summer monsoon (Kansakar *et al.*, 2004; Sharma *et al.*, 2020b). The windward side of the central mid-hill areas receives the highest amount of precipitation (Chen *et al.*, 2021). In the winter season (Fig. 2a), the windward side of western highlands in the central region experiences the highest precipitation intensity, exceeding 0.06 mm/hr. Conversely, the eastern part of the country observes the lowest intensity, below 0.03 mm/hr. This pattern is generally due to the influence of westerly wind disturbances in the winter season, which primarily affect the western region first (Hamal *et al.*, 2020b).

During the pre-monsoon season (Fig. 2b), the eastern part of Nepal experiences higher precipitation intensity, with higher values reaching up to 0.15 mm/hr. In contrast, the western and central parts exhibit relatively lower intensities during this period. As the monsoon season progresses (Fig. 2c), the precipitation distribution shifts, with higher intensities observed in the eastern and central parts of the country. The intensity gradually increases, reaching up to 0.07 mm/hr in the mid and low-elevation areas of these regions. This increase in intensity is attributed to moisture transfer from the Bay of Bengal, which initiates precipitation from the eastern region (Sharma *et al.*, 2020b). In the following, the post-monsoon season (Fig. 2d) records the lowest precipitation intensity among all seasons, with the highest values still observed in the eastern region. On an annual scale (Fig. 2e), the intensity pattern generally reflects that of the monsoon season, with average values below 0.25 mm/hr.

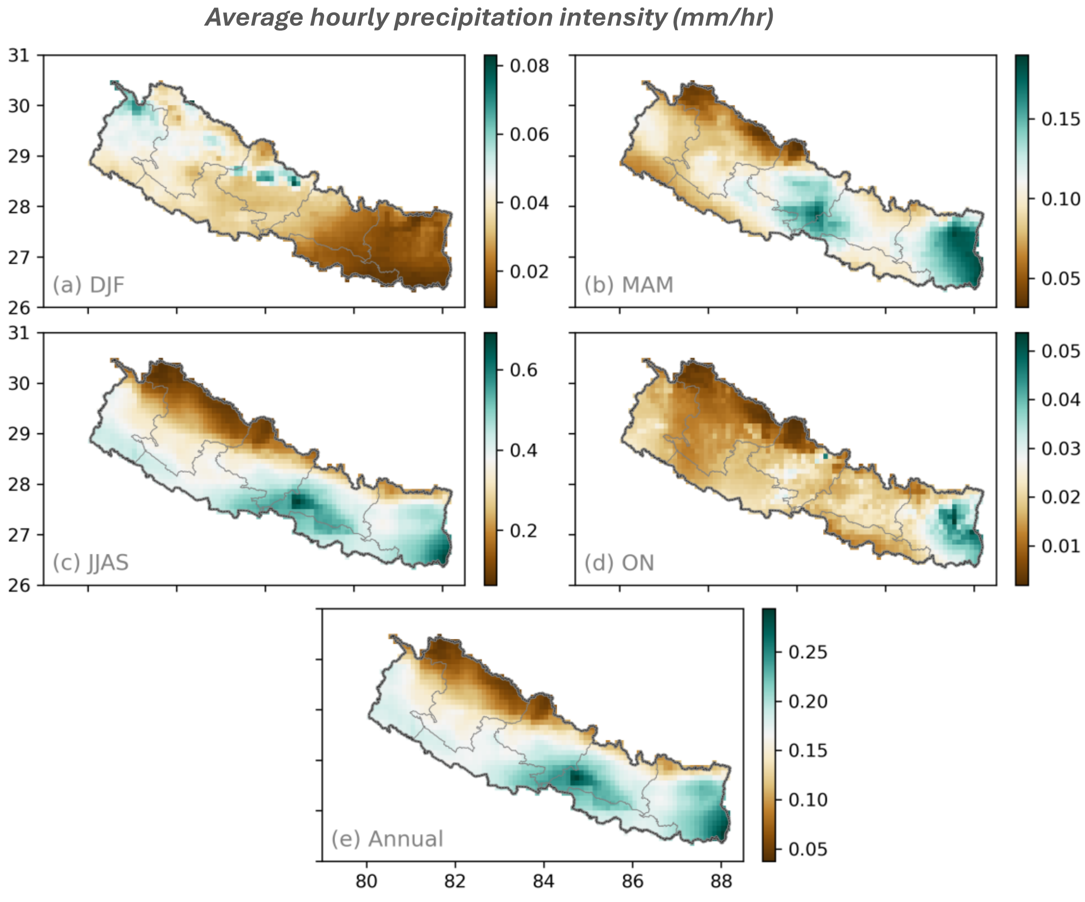


**Figure 2. Spatial distribution of average hourly precipitation intensity (mm/hr) for (a) winter (DJF), (b) spring (MAM), (c) summer (JJAS), (d) autumn (ON), and (e) annual mean during 2015 to 2021 over Nepal.**

To gain a deeper understanding, we calculated the 99th percentile threshold value for extreme hourly precipitation in Nepal. Since the highest intensity and precipitation totals occur predominantly during the monsoon season, we also computed these extremes for each season, as shown in Fig. 3. The spatial distribution of extreme precipitation intensity closely mirrors the average intensity distribution, with similar peak intensity hotspots. These hotspots align with the heavy precipitation events reported in Fig. 1. However, it is important to note that Fig. 1 represents the total incidents reported in the DRR portal from 2011 to the present, while the extremes presented in Fig. 3 cover the period from 2015 to 2021. Additionally, incidents such as landslides are not confined to these extreme precipitation hotspots; they also occur downstream of heavy precipitation areas. The concentration of flood-prone regions in the eastern part of the country can be observed in both the annual extreme intensity in Figs. 2e and 3e. This distribution may be attributed to the influence of orographic effects (Sharma *et al.*, 2021b), where mid-elevation areas experience enhanced precipitation due to the uplift and cooling of moist air masses. Additionally, the topography of the central region and prevailing weather systems likely contribute to the higher frequency of hourly events (Hamal *et al.*, 2021a; Pokharel *et al.*, 2019). This analysis underscores the significant influence of seasonal wind patterns and topography on precipitation distribution in Nepal, with the highest intensities during the monsoon season and notable variations across different seasons in different regions.

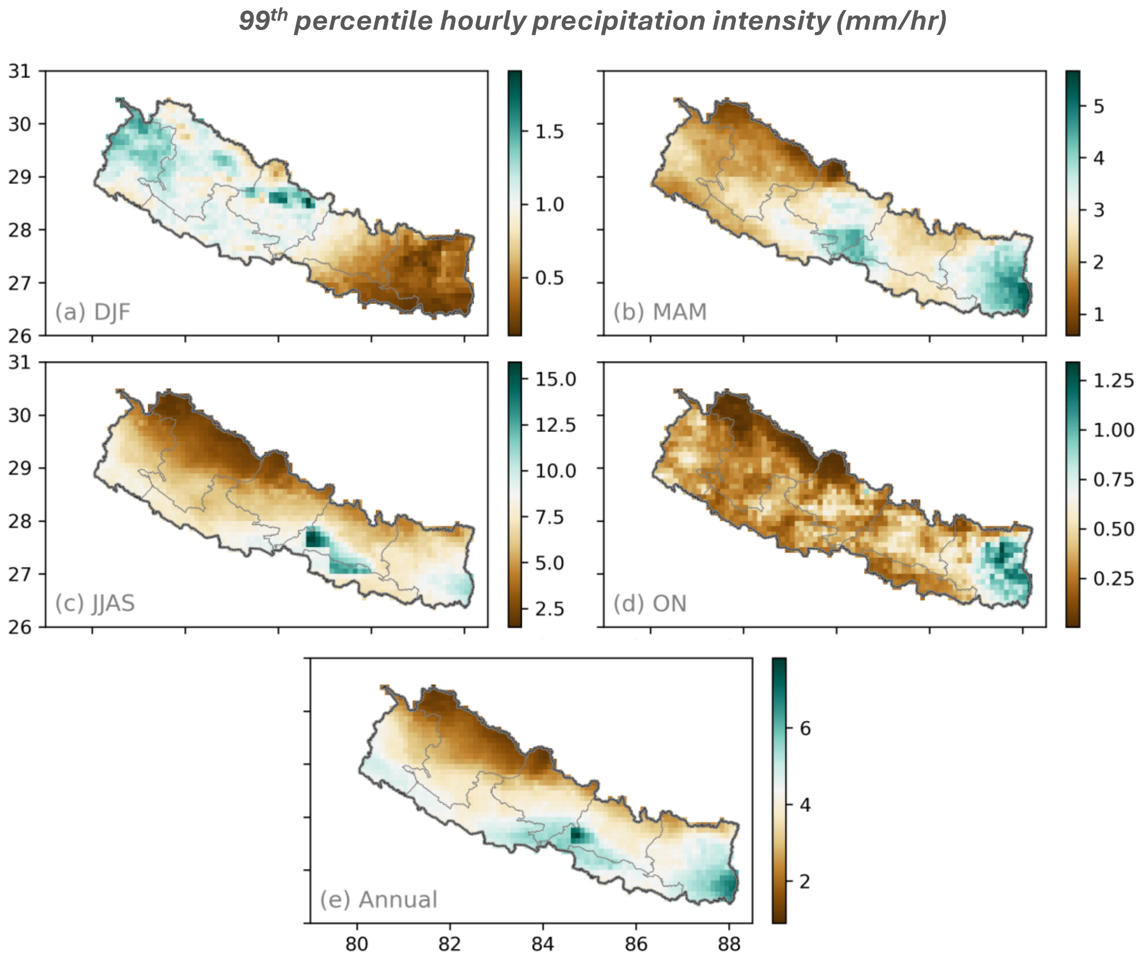


**Figure 3. Spatial distribution of extreme (99th percentile) hourly precipitation intensity (mm/hr) for winter (DJF), b spring (MAM), c summer (JJAS), d autumn (ON), and (e) annual mean during 2015 and 2021 over Nepal.**

**Diurnal cycle of precipitation and extreme**

The distribution of the diurnal cycle of precipitation in Nepal has not been explicitly explored, limiting our understanding of daily temporal precipitation patterns. Here, Fig. 4 presents the average diurnal cycle of precipitation from 2015 to 2021. The pattern indicates that while there is a slight variation in the precipitation amount across different years, the overall trend remains consistent. Since the precipitation in the 2021 monsoon was much higher compared to the last 30-year climatology (Sharma *et al.*, 2023), the hourly distribution in 2021 also shows the highest in the morning and afternoon. Precipitation peaks around midnight, exceeding 0.6 mm/hr, then gradually decreases until late morning, reaching its lowest precipitation of 0.2 mm/hr around 10 am. Subsequently, precipitation begins to increase in the afternoon, maintaining a steady level until approximately 8 pm, after which it starts to rise again. This pattern is likely driven by nocturnal convection, temperature variations, and mountain-valley wind interactions, reflecting the complex interplay of meteorological factors in the region (Kansakar *et al.*, 2004; Pokharel *et al.*, 2019; Talchabhadel *et al.*, 2018).

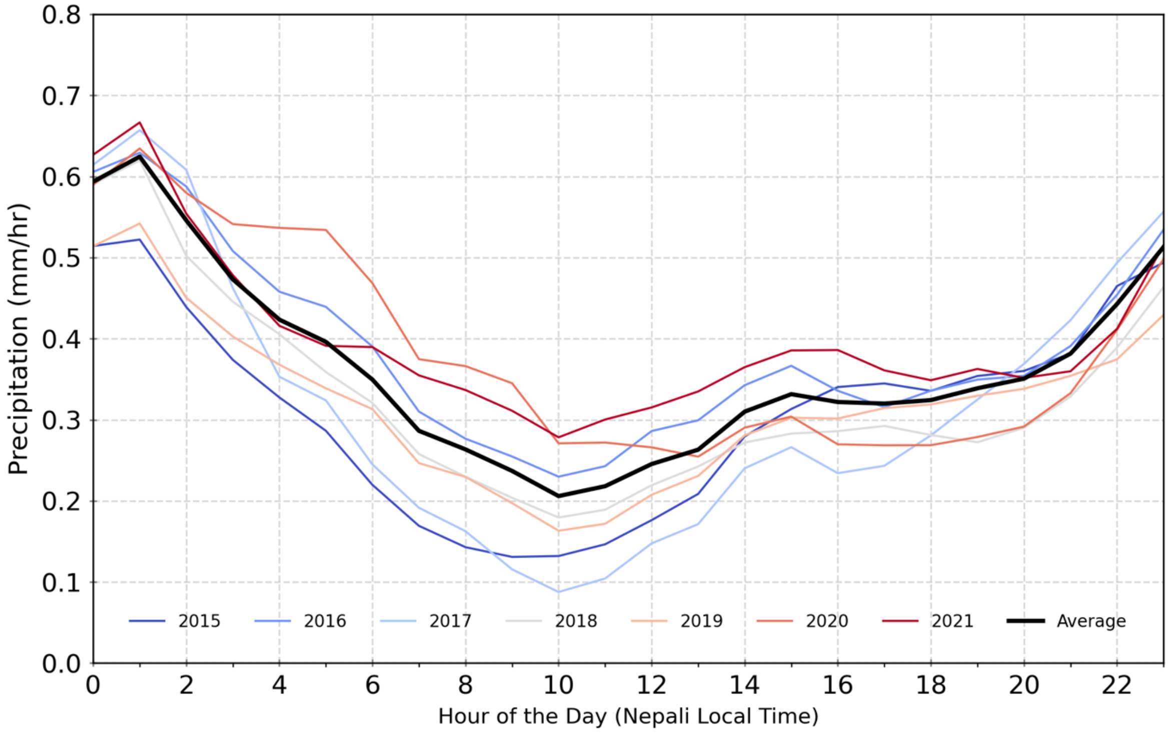


**Figure 4. Diurnal cycle of precipitation during the monsoon season from 2015 to 2021 over Nepal. Different colors represent individual years, while the black color denotes the average precipitation cycle among all years.**

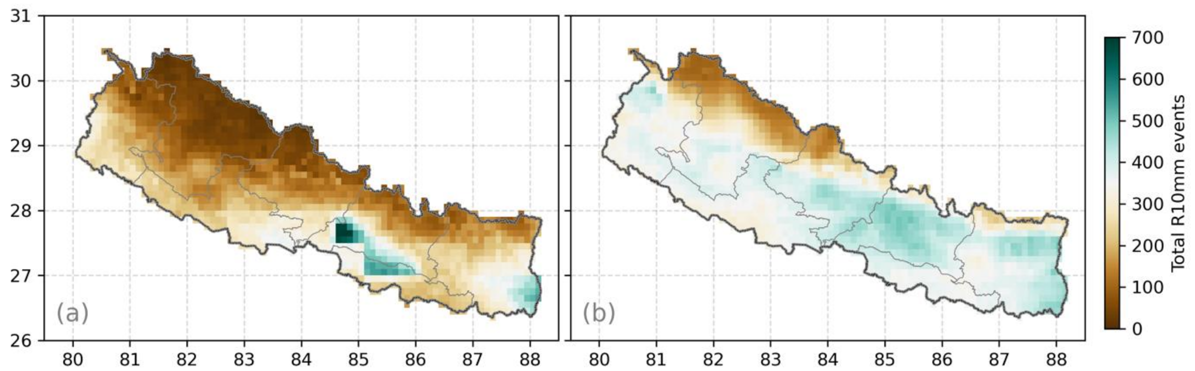


**Figure 5. Total number of heavy precipitation events (R10 mm) for (a) hourly time scale and (b) daily time scale during the monsoon season from 2015 to 2021.**

Figure 5 displays the spatial distribution of total heavy precipitation events on both hourly and daily timescales between 2015 and 2021. It reveals significant spatial variation in the occurrence of these events. The temporal patterns exhibit similarities (not shown), with higher extremes in the hourly distribution as they get aggregated within the same day.

The hourly distribution (Fig. 5a) shows more than 600 heavy precipitation events in the mid- and low-elevation areas of the central region. This high frequency of events contrasts with the daily timescale (Fig. 5b), where the event count is markedly lower for the same regions. The daily distribution in Fig. 5b highlights a higher number of heavy precipitation events around the mid-elevation areas of the central and eastern regions, but this number is much lower (below 500 events).

Interestingly, in the western part of the country, the distribution of heavy events is much lower, which further extends to high-elevation areas of the central and eastern regions. However, in the daily distribution, this low extreme count is only located in the high-elevation areas of the western region. This distribution pattern differs from the hourly timescale, suggesting distinct meteorological and topographical influences on precipitation dynamics. The discrepancy between hourly and daily distributions underscores the importance of temporal resolution in understanding precipitation variability and its potential impacts on the region. Additionally, the variation in hourly and daily extremes indicates that the findings based on daily data cannot be directly extrapolated to hourly resolutions.

## CONCLUSIONS

This study investigates the spatio-temporal seasonal distribution of hourly precipitation in Nepal utilizing IMERG data from 2015 to 2021. The results show that the monsoon season has the highest precipitation intensity, reaching up to 0.7 mm/hr, followed by the pre-monsoon season with intensities up to 0.2 mm/hr. These high-intensity precipitation events are predominantly concentrated in mid- and low-elevation areas of the central and eastern regions. In contrast, the post-monsoon and winter seasons show patches of high-intensity precipitation in high-elevation areas of the western, central, and eastern edges of the country. The annual distribution of hourly precipitation closely mirrors the monsoonal pattern since the monsoon contributes significantly to the total annual precipitation. Extreme precipitation events ($99^{th}$ percentile of wet days), characterized by intensities exceeding 15 mm/hr, also follow this seasonal distribution, peaking during the monsoon season. Further, the diurnal cycle of monsoonal precipitation reveals unique and distinct characteristics, with the highest precipitation rates occurring around midnight and gradually decreasing until late morning. Precipitation rates then increase in the afternoon, maintaining steady levels until around 8 pm, before rising again.

Furthermore, the study compares hourly heavy precipitation extremes with daily extremes (defined as precipitation events exceeding 10 mm/hr). The analysis reveals a higher frequency of hourly heavy precipitation events compared to daily events, highlighting the potential hazards associated with short-term intense precipitation. The spatial distribution of these heavy extremes varies and requires further investigation of the phenomenon. This study suggests the necessity of further research to understand patterns and trends in hourly extreme precipitation and their potential impacts.

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## AUTHOR CONTRIBUTIONS

Conceptualization, B.D.; methodology, D.L.; formal analysis, B.D., D.L., D.R.; investigation, D.L, A.B, C.B.S, S.G.; writing draft, D.L., D.R, A.B., C.B.S, S.G.; review, editing, supervision, B.D. All authors have read and agreed to the published version of the manuscript.

## CONFLICTS OF INTEREST

There is no conflict of interest among the authors.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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