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Research Article

ANALYZING EXTREME PRECIPITATION DURING THE PROLONGED SUMMER MONSOON OF 2022 IN NEPAL: INSIGHTS FROM HOURLY OBSERVATIONAL DATA

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ABSTRACT

The South Asian Summer Monsoon is a vital part of the broader Asian monsoon system, heavily influencing atmospheric circulation, regional climate, and water resources across South Asia. Nepal, located on the southern slopes of the Himalayas, receives approximately 80% of its annual rainfall during the summer monsoon (June-September), which significantly impacts agriculture, water availability, and disaster risks. This study focuses on analyzing the diurnal variation, spatial distribution, and intensity of extreme precipitation events in Nepal during the 2022 monsoon season. Using hourly precipitation data from 63 meteorological stations across Nepal, the study investigates rainfall patterns from June to September 2022. The monsoon season of 2022 began earlier than usual on June 5th, extending for 134 days, the longest on record in Nepal. Despite its extended duration, the total rainfall was not significantly higher than average, with western Nepal experiencing below-normal precipitation and eastern regions receiving slightly above-normal rainfall. The analysis of spatial variation revealed considerable disparities in rainfall distribution, with the Lumle area recording the highest precipitation (3133 mm) and several western districts observing minimal rainfall. Diurnal analysis highlighted a consistent pattern of nighttime precipitation dominance, with the highest rainfall occurring around 9 PM and the lowest around 6 AM. Approximately 60% of the total monsoon rainfall occurred during nighttime hours. This diurnal cycle was consistent across Nepal's major regions, suggesting large-scale atmospheric influences like monsoon troughs and southwesterly winds. The study also assessed extreme precipitation events, defined as rainfall exceeding 40 mm/h. These events were widespread across Nepal, with central and eastern regions experiencing a higher frequency of extreme rainfall compared to western areas. The findings emphasize significant spatial variability in precipitation intensity and duration, critical for understanding regional monsoon dynamics and improving disaster preparedness.

Keywords: Extreme precipitation, diurnal variation, monsoon, Nepal, station data

INTRODUCTION

The South Asian Summer Monsoon (SASM) is a critical component of the larger Asian monsoon system (Ding *et al*., 2007) and plays a vital role in large-scale atmospheric circulation (Fan *et al*., 2017). SASM is characterized by a monsoon trough extending across the Indo-Pakistan plains (Blanford, 1886), with lower-level westerlies driven by surface moisture convergence (Joseph and Raman, 1966), and an upper-level easterly jet stream (Koteswaram, 1950). The intensity of the monsoon is typically measured by monsoon circulation indices and the occurrence of heavy monsoon rainfall (Fan *et al*., 2017).

The onset of the summer monsoon triggers rapid atmospheric transitions, often within 1–2 weeks (Wu *et al*., 1998), with monsoon rains and significant seasonal changes in low-level winds (Krishnamurti *et al*., 1982). According to Lau and Yang (1996), the earliest sign of onset is the northward movement of convection over Indo-China, followed by a rapid shift in the Inter Tropical Convergence Zone (ITCZ) in mid-May. This shift is influenced by sea surface temperature anomalies in the Indian Ocean (Joseph *et al*., 1994). Additionally, the upper-tropospheric zonal momentum budget (Schneider and Bordoni, 2008) and thermal contrasts (Sun *et al*., 2010; Dai *et al*., 2013) also play a crucial role, with circulation variability being a more dominant factor than moisture variability (Walker *et al*., 2015). A transient local Hadley cell, possibly associated with the MJO (Wu *et al*., 1998), sustains the northward-moving monsoon cloud bands (Yasunari, 1981). Wu *et al*. (1998) also found that the Somali jet intensifies only after the ITCZ crosses the Indian Ocean, while Chen and Yen (1986) observed changes in the Somali jet's 40–50-day signal corresponding to the monsoon trough.

The South Asian Summer Monsoon (SASM) is driven by land–ocean thermal contrasts and pressure gradients, enhanced by meridional temperature gradients, latent heating, orography, and moisture transport via Somali and East African jets (Fasullo & Webster, 2003; Houze Jr, 2012; Liu *et al*., 2012). Blocking highs over northern Europe coincide with monsoon onset (Flohn *et al*., 1957). SASM is strongly linked to ENSO; negative SOI years correlate with reduced rainfall in Nepal, while positive SOI years bring more precipitation (Shrestha *et al*., 2000; Sharma *et al*., 2020a). SASM delivers 70–75%

of annual rainfall in the region, with Nepal receiving ~80% during June–September (Fan *et al*., 2017). Spatial variability is high, and intense rainfall often causes floods and landslides, risks that are growing with climate extremes (Shrestha *et al*., 2000; Sharma *et al*., 2020b). This study aims to analyze the diurnal variation of monsoon precipitation, its spatio-temporal patterns, and high-intensity extreme precipitation events in Nepal, particularly focusing on monsoon of 2022. Investigating the diurnal variation of precipitation for the first time will provide insights into precipitation patterns and the frequency of extreme events.

MATERIALS AND METHODS

Study Area

Nepal is divided into five main physiographic regions: the Terai, Siwaliks, Middle Mountains, High Mountains, and High Himalayas (Kansakar *et al*., 2004; Sharma *et al*., 2020b; Shrestha *et al*., 2020) and seven provinces that are Sudurpashchim, Karnali, Lumbini, Gandaki, Bagmati, Madhesh and Koshi (Figure 1a). These regions are further grouped into three broader zones: Lowlands (Terai and Siwaliks), Hills (Middle and High Mountains), and High Mountains (High Himalayas), according to Karki *et al*. (2015).

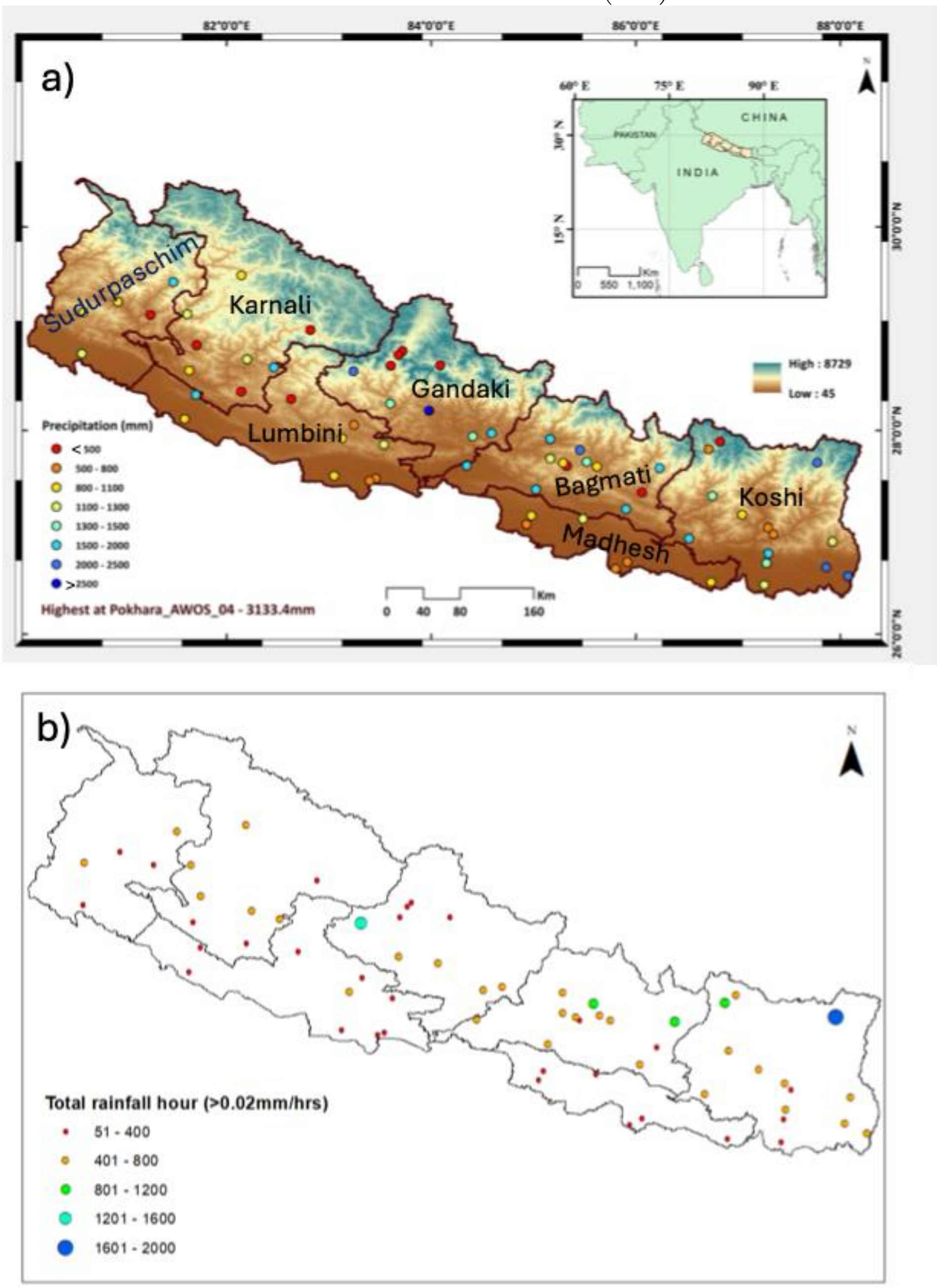

Figure 1. Upper panel a) shows study area and the selected meteorological stations with the total rainfall in monsoon from June to September 2022, the background color is the terrain elevation and inserted map is the map of South Asia with Nepal in yellow color. Lower panel b) shows total precipitation hours during the summer monsoon 20222 based on the precipitation threshold larger than 0.02 mm/h.

Situated on the southern slopes of the Himalayas, Nepal's climate is strongly influenced by the South Asian monsoon system (Baidya *et al*., 2008). The Bay of Bengal branch of the southwest monsoon brings the summer monsoon to Nepal. Between 1971 and 2012, the country experienced an average annual precipitation of 1850 mm and an average temperature of 20°C (DHM, 2015).

Data and Methods

In this study, we utilized hourly precipitation data from 63 automatic weather stations (AWS) distributed across Nepal for the 2022 summer monsoon season (June to September) (Figure 1). The recent expansion of the AWS network by the Department of Hydrology and Meteorology (DHM), Government of Nepal, has enabled more detailed analysis of precipitation variability and extremes at sub-daily timescales—an improvement over traditional daily-scale data.

To ensure the reliability of the dataset, a rigorous quality control procedure was implemented. Initial checks included the identification and removal of duplicate timestamps, negative precipitation values, and physically implausible outliers (e.g., hourly rainfall exceeding 100 mm without supporting nearby station evidence). Stations with more than 20% missing data during the study period were excluded from the analysis to maintain temporal consistency. Missing values within the retained stations were not gap-filled but instead excluded from aggregation calculations.

Following quality control, 63 stations with at least 80% data completeness and good spatial coverage—including representation from lowland, mid-hill, and mountainous regions—were selected. Hourly precipitation values were aggregated into daily and monthly totals to assess temporal patterns, including seasonal and regional variability in rainfall across Nepal.

Additionally, we computed intensity-related extreme precipitation events from June to September 2022 by using four hourly precipitation rate indicators: R1, R10, R20, and R40 mm/hour. These represent the average hours when precipitation rates were <10 mm/h, ≥ 10 mm/h, ≥ 20 mm/h, and ≥ 40 mm/h, respectively, over the study period. We also utilized the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) gridded monthly precipitation dataset, which has been previously applied in studies over Nepal (Nepal *et al*., 2024). The monthly and monsoon anomaly for 2022 was calculated by comparing it to the 30-year average using Climate Hazards Center InfraRed Precipitation with Station (CHIRPS) data.

RESULTS

The 2022 monsoon season in Nepal commenced earlier than the usual onset date of June 13th, beginning instead on June 5th. It extended until October 16th, marking the longest monsoon in Nepal's recorded history, lasting a total of 134 days. Despite the extended duration, the overall monsoon rainfall was not significantly higher than normal. Most of the western regions experienced below-normal precipitation, while the eastern region received slightly above-normal rainfall. A detailed analysis of these patterns is provided in a subsequent section.

Spatial Variation of Monsoon 2022 Rainfall

The spatial distribution of precipitation for the 2022 monsoon, as illustrated in Figure 1a, follows a pattern similar to the annual distribution observed in previous studies (Sharma *et al*., 2020a; Sharma *et al*., 2021a; Sharma *et al*., 2021b). The figure highlights significant variability in rainfall across Nepal. The highest precipitation was recorded in the Lumle area, reaching 3133 mm, while the lowest was observed in the western districts of Achham (10.2 mm), Manang (164 mm), and Mustang (107 mm). It is noteworthy that the areas with the lowest rainfall are predominantly located in the western part of Nepal, a finding consistent with previous studies (Sharma *et al*., 2020a; Sharma *et al*., 2021a; Sharma *et al*., 2021b; Pokharel *et al*., 2019).

Interestingly, the Solukhumbu district in Eastern Nepal (Koshi Province) also recorded one of the lowest rainfall totals, with only 319 mm, deviating from the usual pattern in the east. However, other parts of Eastern Nepal, particularly the northern region near Taplejung and the southern region around Jhapa, experienced significantly higher rainfall during the 2022 monsoon. In contrast, the Terai region of Madhesh Province, specifically the eastern part of the central Terai, received less rainfall compared to the broader eastern region. This uneven distribution across the country, particularly the stark contrast between the wetter eastern and drier western regions, underscores the complex spatial variability of Nepal's monsoon system, which aligns with the findings of previous research (Pokharel *et al*., 2019).

Figure 1b presents the total number of precipitation hours recorded at various stations included in this study. The longest duration was observed at Num, Sankhuwasabha (Koshi Province), with approximately 2000 hours of precipitation. In contrast, most stations in the Tarai region (southern plains of Nepal) experienced less than 400 hours of precipitation. A few stations in the Bagmati and Koshi regions recorded around 1500 hours of precipitation, while most stations in the midhills received less than 800 hours. These findings suggest that the Tarai region experienced fewer hours of precipitation compared to the midhills during the summer monsoon of 2022.

Monsoon 2022 Precipitation Anomaly

The 2022 monsoon season in Nepal presented notable variability in rainfall patterns, impacting different regions and months unevenly, as depicted in Figure 2. June saw central and eastern regions, including Bagmati, Madhesh, and Koshi Provinces, receiving above-normal rainfall, which likely supported early-season agricultural activities. Conversely, the western areas like Karnali and Sudurpashchim Provinces experienced below-average precipitation, setting a precedent for potential drought conditions. July further exacerbated this trend with widespread negative rainfall anomalies across the Terai of Koshi, Lumbini, Gandaki, and parts of Karnali Provinces, marking what is typically the peak of the monsoon with concerning dry spells that could significantly affect crop yields and water availability.

August continued the pattern of dry conditions in the west, while some eastern locales observed above-normal rainfall, underscoring the distinct east-west contrast in monsoon behavior. By September, a reversal occurred with western and central regions including Gandaki and Lumbini Provinces receiving more than average rainfall, whereas the eastern regions saw reduced precipitation. The overall positive anomalies in the Terai and more balanced rainfall in the hilly areas against the ongoing deficits in mountainous regions suggest a complex interplay of climatic factors. The late surge in rainfall, beneficial in some aspects, may not have fully compensated for the earlier shortages in critical agricultural timelines.

The 2022 monsoon season in Nepal exhibited significant spatial variability in rainfall patterns, as illustrated in Figure 3. The season's overarching patterns reveal a critical disparity across the country, with persistent drought conditions plaguing western regions, particularly Karnali and Sudurpashchim Provinces, while central and eastern regions experienced fluctuating rainfall throughout the season. This stark contrast underscores the complex nature of Nepal's climate system and highlights the challenges in managing water resources and agricultural planning at a national level. The western regions' prolonged dry spell likely had severe impacts on agricultural productivity, water availability, and socio-economic conditions of communities reliant on rain-fed agriculture. In contrast, the central and eastern regions faced a different set of challenges due to the alternating periods of excess and deficit rainfall, potentially affecting crop yields and water management strategies.

Diurnal Variation of Precipitation

The diurnal variation of rainfall during the summer monsoon of 2022 in Nepal reveals notable temporal patterns, highlighting the prevalence of nighttime precipitation. Figure 4 clearly shows that while rainfall occurred consistently throughout the day, there is a pronounced peak during the nighttime hours, particularly around 9 PM. This peak suggests that atmospheric conditions conducive to rainfall, such as cooling temperatures and moisture accumulation, are more favorable in the late evening. The lowest recorded rainfall, occurring around 6 AM, aligns with the natural diurnal cycle, where early morning hours experience lower temperatures and less atmospheric instability, typically suppressing rainfall. Interestingly, a secondary, smaller peak is observed around 10 AM, potentially corresponding to the mid-morning rise in temperatures, which may lead to localized convection and brief rainfall events. However, this morning peak is significantly less pronounced than the main nighttime peak.

A breakdown of the monthly rainfall patterns reveals that June, marking the onset of the monsoon season, shows the greatest diurnal variation. The significant fluctuation in June's rainfall patterns can be attributed to the early monsoon phases, where atmospheric dynamics are more variable. In contrast, September, marking the end of the monsoon, demonstrates the least variation, likely due to stabilizing atmospheric conditions as the monsoon weakens and the seasonal transition to autumn begins.

On a broader scale, approximately 40% of the total rainfall occurred during the daytime (6 AM to 6 PM), while a dominant 60% took place during the nighttime (6 PM to 6 AM). This finding reinforces the idea that nighttime conditions are more favorable for rainfall during the summer monsoon in Nepal. A recent study by Dawadi *et al.* (2024) also shows similar results, with more precipitation occurring at night during the monsoon season. They utilized satellite-measured precipitation data, which shows a different peak precipitation time (1:00 AM local time) compared to the results from this study (9:00 PM).When analyzing the diurnal variation of rainfall across the three major regions of Nepal—western, central, and eastern—the data indicates a remarkably consistent pattern. The regional rainfall distribution mirrors the overall national average, suggesting that the diurnal cycle of rainfall is not significantly influenced by geographical differences within Nepal. The uniformity across regions may be explained by the dominance of large-scale atmospheric circulation patterns, such as the monsoon trough and moisture-laden southwesterly winds, which affect the entire country uniformly.

The results suggest that the diurnal variation of summer monsoon rainfall in Nepal is characterized by a dominant nighttime peak in precipitation, consistent regional patterns, and a higher percentage of nighttime rainfall across the entire monsoon period.

Variation of Extreme Precipitation

Figure 5 illustrates the spatial variation of different precipitation intensities during the monsoon months (June to September) across Nepal. Precipitation frequencies are categorized into four intensity ranges, with extreme precipitation defined as events exceeding 40 mm/h. Extreme precipitation was recorded in all provinces for at least one hour. Notably, two stations in Sudurpaschim Province recorded extreme precipitation once (Figure 5a), while one station in Karnali Province recorded two occurrences. Lumbini Province had a station with five events, and in Gandaki Province, one station recorded nine occurrences. In Bagmati Province, a station recorded four events, while in Madhesh Province, three stations observed extreme precipitation twice. Koshi Province recorded the highest frequency, with one station observing eight events of precipitation exceeding 40 mm/h.

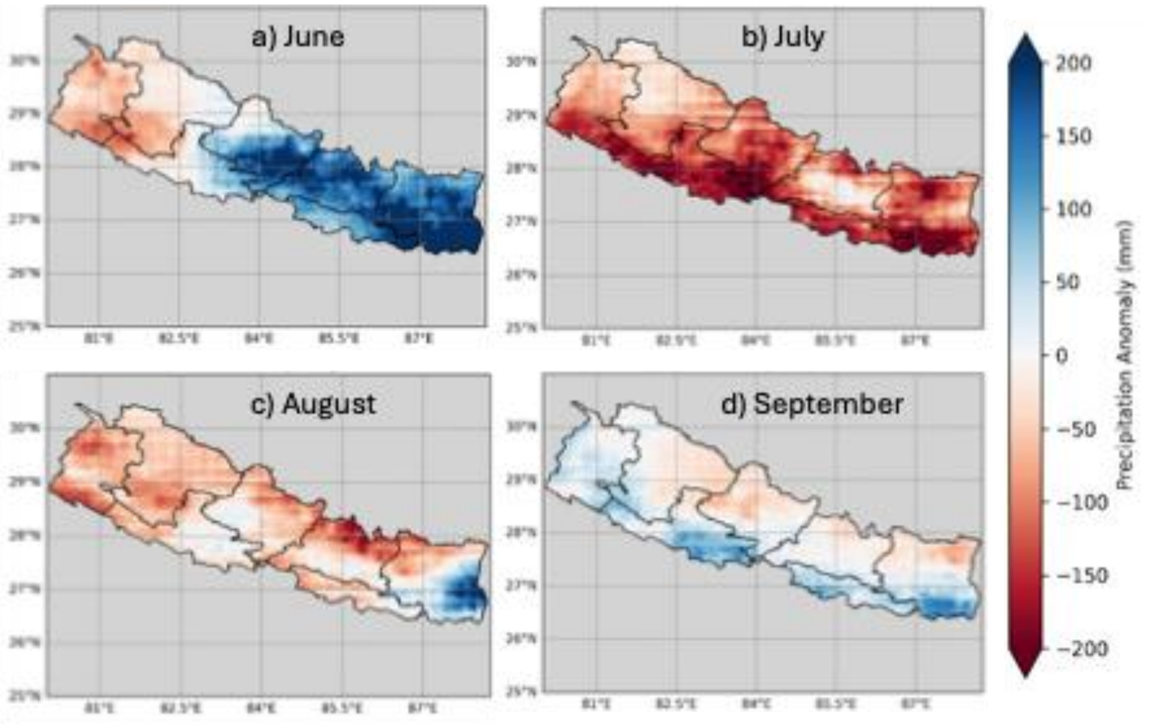

Figure 2. Precipitation anomaly during a) June, b) July, c) August, and d) September 2022 compared to average precipitation from 1990 to 2020 during each month. The CHIRPS monthly precipitation data are used to calculate the precipitation anomaly in Nepal.

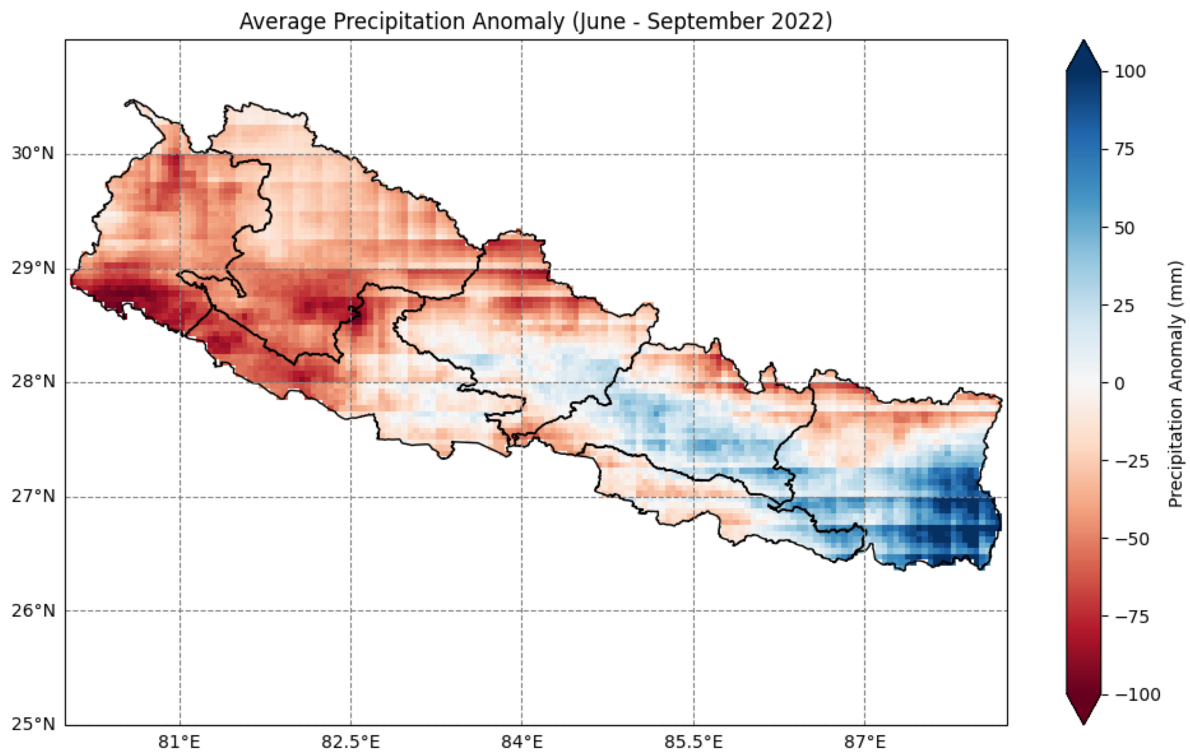

Figure 3. Same as Figure 2, but precipitation anomaly in Nepal during the summer monsoon (June to September) of 2022.

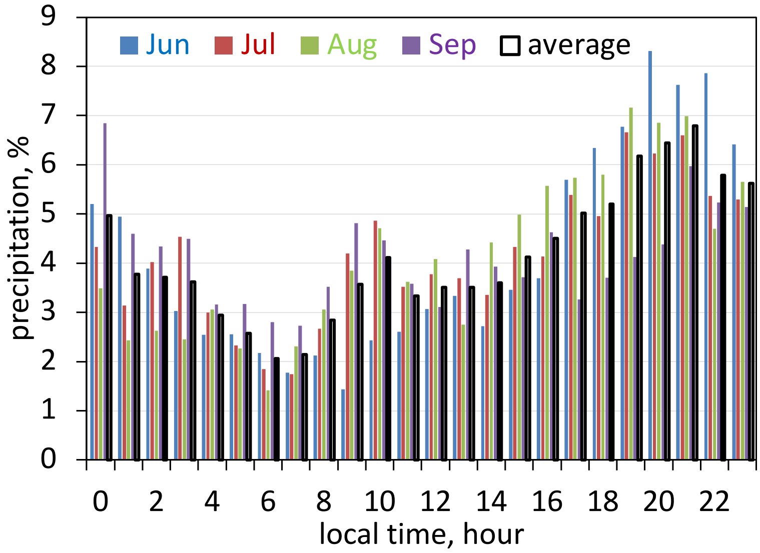

Figure 4. Diurnal variation of summer monsoon precipitation as a percentage of total monsoon precipitation for the months of June (blue bars), July (red bars), August (green bars), September (purple bars) and monsoon average (black bars).

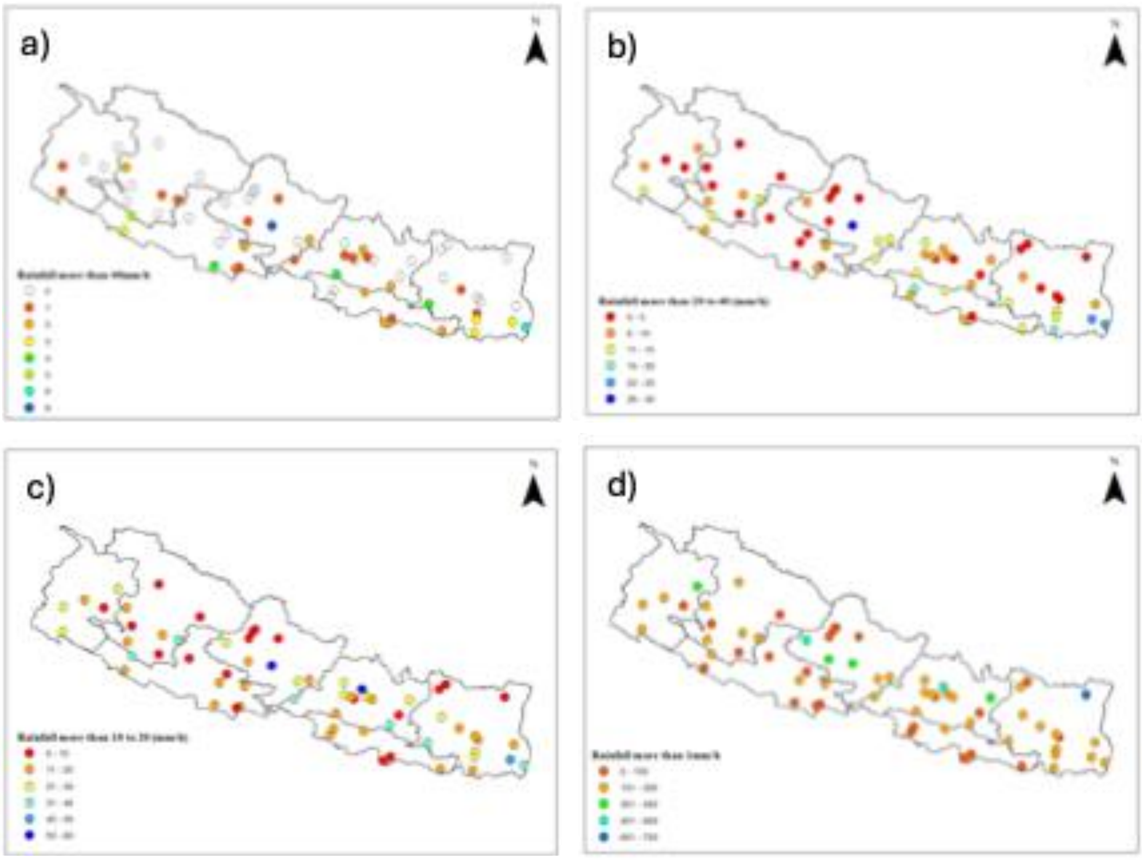

Figure 5. Spatial distribution of total hours of different rainfall intensity during monsoon 2022. The upper left panel a) shows the frequency of precipitation intensity larger than 40 mm/h, upper right panel b) shows the frequency of precipitation intensity of 20 to 40 mm/h, lower left panel c) shows the frequency of precipitation intensity of 10 to 20 mm/h, and lower right panel d) shows the precipitation intensity of less than 10 mm/h based on the hourly observed data for the selected stations.

Precipitation with intensities ranging from 20 to 40 mm/h, classified as very heavy precipitation, was recorded across all stations, though with lower frequencies in western Nepal compared to the eastern regions (Figure 5b). Several stations experienced this intensity for approximately 5 to 10 hours (indicated by red dots), while others recorded up to 15 hours (yellow dots). Only two stations registered this intensity for 20 hours (light blue dots), while two stations in the Koshi region recorded it for around 25 hours (sky-blue dots). A station in Gandaki Province (Pokhara) notably recorded around 30 hours of precipitation at this intensity.

Similarly, heavy precipitation with intensities between 10 and 20 mm/h (Figure 5c) exhibited comparable spatial variability, with higher frequencies in eastern and central Nepal and lower frequencies in the western regions. Light precipitation, defined as rainfall with intensities between 1 and 10 mm/h, is shown in Figure 5d. Most stations recorded fewer than 300 hours of light precipitation during the monsoon season. However, a few stations across all provinces recorded between 300 and 600 hours, with one station in the Koshi region (Num) recording more than 600 hours of light precipitation.

These findings indicate that extreme precipitation events were widespread across Nepal during the 2022 monsoon, occurring at least once in every province. However, central and eastern provinces experienced a higher frequency of extreme and heavy precipitation events compared to western regions. This result is aligned with the recent extreme precipitation study by Dawadi *et al.* (2024). This highlights a significant spatial variability in the intensity and duration of precipitation across the country during the monsoon season, revealing important regional differences in monsoon dynamics.

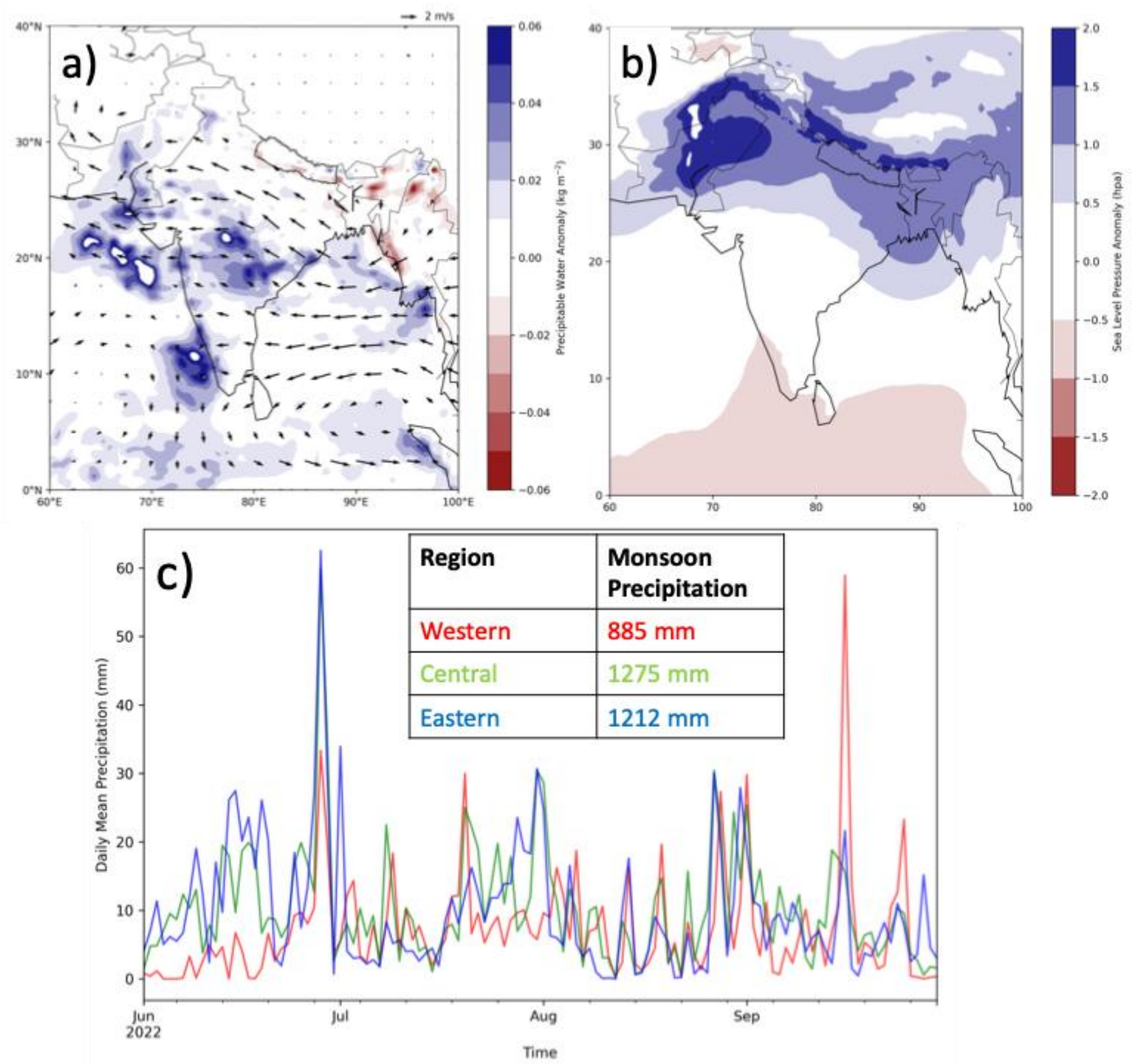

Figure 6. Large-scale synoptic conditions and daily rainfall over Nepal during the 2022 summer monsoon season (June–September). (a) 850 hPa wind anomalies (vectors) and total precipitable water anomalies (shaded); (b) sea level pressure (SLP) anomalies; (c) daily average precipitation over western (80°–83°E), central (83°–85°E), and eastern (85°–88°E) Nepal. The inset table in c) shows the mean precipitation for each region.

DISCUSSION

During the 2022 monsoon season, Nepal experienced above-normal rainfall, primarily driven by the combined influence of a moderate La Niña and a strong negative Indian Ocean Dipole (IOD) (Sharma *et al.*, 2020a). NOAA's Oceanic Niño Index (ONI) showed persistent negative sea surface temperature anomalies in the Niño 3.4 region (−0.7 °C to −1.1 °C), indicative of a moderate La Niña event, which is typically associated with enhanced monsoonal activity over South Asia. Concurrently, the Dipole Mode Index (DMI) exhibited a strong negative phase (reaching −1.17 °C) from June to September, enhancing moisture transport from the Bay of Bengal. This coupled ocean–atmosphere configuration contributed to wetter-than-average conditions across much of Nepal, particularly in the central and eastern regions, as reported by the DHM and regional climate outlooks.

To further investigate the spatial variability of rainfall, we analyzed large-scale synoptic conditions and total precipitable water during the 2022 summer monsoon (Figure 6). While central and eastern Nepal received above-average rainfall, consistent with the La Niña influence, western Nepal and most parts of the Tarai experienced below-average precipitation (Figure 3). Synoptic analysis revealed that strong low-level monsoonal winds and increased total precipitable water were concentrated over central and southern India (Figure 6a), while anomalously high sea level pressure (SLP) over Nepal (Figure 6b) suppressed precipitation, particularly in the western region. Moreover, the delayed monsoon onset in western Nepal—where significant rainfall began only in the last week of June (Figure 6c)—further reduced seasonal totals. Although the monsoon officially commenced on 5 June 2022 in eastern Nepal, its advancement into western Nepal was significantly delayed. These findings suggest that, while La Niña generally favors enhanced monsoon rainfall over Nepal, it does not ensure uniform distribution across the country. The observed spatial disparity in precipitation aligns with earlier findings of extreme regional variability during La Niña years (Pokharel *et al.*, 2019). Average precipitation was substantially lower in western Nepal compared to the central and eastern regions, as indicated by the inset table in Figure 6c.

CONCLUSIONS

The 2022 monsoon season in Nepal was unprecedented in both its duration—lasting 134 days, the longest on record—and its early onset, occurring eight days ahead of the usual schedule. Despite this extended monsoon period, the total rainfall was not significantly higher than average. However, what made this season particularly noteworthy was the increased frequency of extreme precipitation events, even though the overall rainfall was lower than in previous years. This study is the first to analyze hourly precipitation data from 63 observation stations across Nepal, focusing on the diurnal variation and spatial distribution of extreme rainfall during the monsoon season (June to September) of 2022. The diurnal analysis revealed two distinct peak periods of rainfall, with the highest precipitation occurring in the early morning across all three major regions of Nepal. Although slight regional differences were observed in the timing of these peaks, the overall pattern highlighted a consistent nighttime precipitation dominance.

The spatial distribution analysis identified the highest rainfall hotspots along the windward side of the Annapurna Himalayan range and in the eastern lowland and high-elevation regions. Notably, 32 of the 63 stations, mostly in mid- and low-elevation areas, recorded extreme rainfall events exceeding 40 mm/h. In a surprising finding, some stations on the leeward side of the Annapurna range, such as Manang's Humde station, also experienced extreme precipitation, with one event reaching 54 mm rain within an hour in September. The highest concentration of extreme precipitation hours occurred in the mid-hill and Terai regions, with Pokhara recording the most frequent extreme events. The increased frequency of extreme rainfall in 2022 had significant consequences, contributing to numerous landslides, floods, and flash floods.

This study's pioneering use of hourly precipitation data offers valuable insights into the variability of rainfall and extreme weather events, providing background information for policymakers, disaster management agencies, and researchers. A limitation of this study is that it focuses on data from a single summer monsoon. However, future research will expand to include longer term hourly precipitation data for more comprehensive analysis to conclude the regions of extreme precipitation and diurnal variation of monsoon rain climatology.

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AUTHOR CONTRIBUTIONS

SA, PL, JK, SM, DR, AM, ST, HKP, SR, AB, SP, and AP contributed to data analysis, visualization, and initial drafting of the manuscript. ES and SS provided critical revisions. DA, TBC, VPP, and BP supervised the research, contributed to editing, and finalized the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

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

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