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The Influence of Weather Patterns and the Madden-Julian Oscillation on Extreme Precipitation Over Sri Lanka

Akshay Deoras[1,2], Andrew G. Turner[1,2], Kieran M. R. Hunt[1,2], and I. M. Shiromani Priyanthika Jayawardena[3]

[1]National Centre for Atmospheric Science, University of Reading, Reading, UK, [2]Department of Meteorology, University of Reading, Reading, UK, [3]Department of Meteorology, Colombo, Sri Lanka

Key Points:

- Extreme precipitation in Sri Lanka occurs most frequently in weather patterns associated with the northeast and second intermonsoon seasons
- In weather patterns with the largest frequency of extreme precipitation events, extreme precipitation can persist for five consecutive days
- The frequency of extreme precipitation events is enhanced in phases 1–4 of the Madden-Julian Oscillation

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

A. Deoras,
akshay.deoras@reading.ac.uk

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Author Contributions:

Conceptualization: Akshay Deoras, Andrew G. Turner, Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena
Data curation: Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena
Formal analysis: Akshay Deoras
Investigation: Akshay Deoras, Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena
Methodology: Akshay Deoras, Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena
Resources: Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena

Abstract Sri Lanka is affected by extreme precipitation events every year, which cause floods, landslides and tremendous economic losses. We use the ERA5 reanalysis data set to understand the association of extreme precipitation events with 30 weather patterns, which were originally derived to represent the variability of the Indian climate during January–December 1979–2016. We find that weather patterns that are most common during the northeast monsoon (December–February) and second intermonsoon (October–November) seasons produce the highest number of extreme precipitation events. Furthermore, extreme precipitation events occurring during these two seasons are more persistent than those during the southwest monsoon (May–September) and first intermonsoon (March–April) seasons. We analyze the modulation of extreme precipitation events by the Madden-Julian Oscillation, and find that their frequency is enhanced (suppressed) in phases 1–4 (5–8) for most weather patterns.

Plain Language Summary Extreme rainfall events affect Sri Lanka every year, causing floods, landslides and tremendous losses. Thus, it is important to identify weather patterns that are associated with these events. Furthermore, it is important to understand how the dominant modes of the tropical intraseasonal variability, such as the Madden-Julian Oscillation, modulate their occurrence. In this study, we use the European Centre for Medium-Range Weather Forecasts ERA5 reanalysis data set to understand the association between extreme precipitation events and a set of 30 weather patterns that were originally derived to understand the variability of the Indian climate. Our results suggest that weather patterns that are most common during winter and autumn seasons produce the highest number of extreme precipitation events in Sri Lanka, and these events are more persistent than those occurring during summer and spring seasons. The frequency of extreme precipitation events is enhanced when the Madden-Julian Oscillation is active over the Indian Ocean.

1. Introduction

Sri Lanka is a compact island in the tropics which witnesses two monsoon seasons each year. The southwest monsoon brings rainfall between May and September, contributing to around 30% of the total annual rainfall, whereas the northeast monsoon (December–February) contributes around 26% of the total rainfall for the country as a whole (e.g., Jayawardena et al., 2020). The bimodal rainfall pattern (Figure 1b) is associated with the movement of the intertropical convergence zone over Sri Lanka (e.g., Suppiah, 1996), with the two rainfall peaks occurring in April and November. Sri Lanka receives around 14% and 30% of the total annual rainfall during the first (March–April) and second (October–November) intermonsoon seasons, respectively. The spatial distribution of rainfall is skewed since the mountainous region in the south-central part (Figure 1a) results in considerable orographic rainfall.

Sri Lanka is vulnerable to devastating floods and landslides every year (Askman et al., 2018), particularly during the October–December period when the frequency of extreme precipitation events (here defined as the number of days on which daily rainfall averaged over the whole country exceeds the 95th percentile on all days between 1979 and 2016) is high (Figure 1b). For example, many parts of the country received over 200 mm rainfall on 15 May 2016, causing more than 200 fatalities and about USD 2 billion in economic losses (Koralegedara et al., 2019; Samantha, 2018). Jayawardena et al. (2020) found that rainfall in Sri Lanka is enhanced (suppressed) in phases 2–3 (6–7) of the Madden-Julian Oscillation (MJO), and the occurrence of extreme rainfall events is enhanced in MJO phases 2–3. Deoras et al. (2021) found that low-pressure systems forming over southern parts of the Bay of Bengal during June–September produce substantial rainfall in Sri Lanka, and the frequency of these

Supervision: Andrew G. Turner, Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena
Validation: Akshay Deoras, Andrew G. Turner, Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena
Visualization: Akshay Deoras
Writing – original draft: Akshay Deoras
Writing – review & editing: Akshay Deoras, Andrew G. Turner, Kieran M. R. Hunt, I. M. Shiromani Priyanthika Jayawardena

weather systems is enhanced in MJO phases 1–2. In fact, low-pressure systems can trigger extreme precipitation events in the country (e.g., Koralegedara et al., 2019). However, unlike for other countries in the region such as India, there has not been any investigation of weather patterns associated with extreme precipitation events in Sri Lanka. It is therefore important to identify such weather patterns and analyze their modulation by the MJO. This analysis is important since the MJO can be well predicted on the sub-seasonal time scale (Vitart, 2017), which could help meteorologists issue warnings to weather-dependent stakeholders such as farmers.

The identification of weather patterns and their applications in weather forecasting are becoming increasingly popular. Their applications rely on the repeated appearance of certain large-scale flow patterns, which persist beyond the lifetime of individual synoptic-systems at fixed geographical locations and thus influence the intra-seasonal variability (Robertson & Ghil, 1999). Weather patterns are identified using different techniques such as the empirical orthogonal function (EOF) analysis and cluster analysis. For the Indian subcontinent, Neal et al. (2020) identified a set of 30 weather patterns that are the most representative of the variability of the Indian climate. They applied a *k*-means clustering technique (MacQueen et al., 1967) to mean sea-level pressure, *u* and *v* winds at 10 m, 925 and 850 hPa at 12 UTC during January–December 1979–2016, for which they used the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis data (Dee et al., 2011). They generated a total of 192 sets of weather patterns, which included variations over 12 geographic domains in South Asia. They found that a set of 30 weather patterns clustered over one of the large continental-sized domains that used 850 hPa winds was the most representative cluster in terms of rainfall variability. The application of these 30 weather patterns need not be confined to India since they also represent the observed large-scale circulation features over Sri Lanka (see Figure 4 of Neal et al., 2020).

In this study, our primary aim is to understand the association between weather patterns and extreme precipitation over Sri Lanka, for which we analyze the 30 weather clusters derived by Neal et al. (2020); our objective is to answer the following questions:

- How do the 30 weather patterns modulate mean precipitation and the frequency of extreme precipitation events in Sri Lanka?
- How persistent is extreme precipitation in Sri Lanka?
- To what extent does the presiding weather pattern play a role in the relationship between the MJO and extreme precipitation over Sri Lanka?

We present an outline of the data and methodology in Section 2. We look at mean precipitation, the frequency and persistence of extreme precipitation events, and the modulation of their occurrence by the MJO in Section 3, and conclude in Section 4.

2. Data and Methods

2.1. ERA5 Reanalysis

We use data from the ECMWF ERA5 reanalysis (Hersbach et al., 2020) to investigate 850 hPa winds and precipitation in the 30 weather patterns during January–December 1979–2016. The ERA5 data is available globally from 1940 at an hourly resolution and on a 0.25° × 0.25° grid. Accumulations are over the hour ending at the validity time. We therefore calculate daily precipitation by summing hourly precipitation accumulations between 01 UTC (day 0) and 00 UTC (day +1; both inclusive). We use a land-sea mask to consider precipitation over the land area of Sri Lanka. If the daily rainfall over Sri Lanka exceeds the 95th percentile of daily rainfall on all days during January–December 1979–2016, we consider that event as an extreme precipitation event. Thus, the precipitation threshold for an extreme precipitation event is 15.6 mm day^{-1}, and extreme precipitation events occurred on 694 of 13,880 days in the analysis period.

Bandara et al. (2022) compared nine gridded precipitation datasets from reanalysis and remote sensing products for meteorological and hydrological applications in Sri Lanka. They inferred that ERA5 had the best performance since it replicated the observed precipitation climatology of Sri Lanka very well. We therefore select ERA5 as the primary data set in this study to analyze rainfall.

2.2. Station Rainfall

We use daily rainfall data from 51 meteorological stations (see Figure 1a) in Sri Lanka to take some account of the observational uncertainty. These stations are operated by the Department of Meteorology, Sri Lanka.

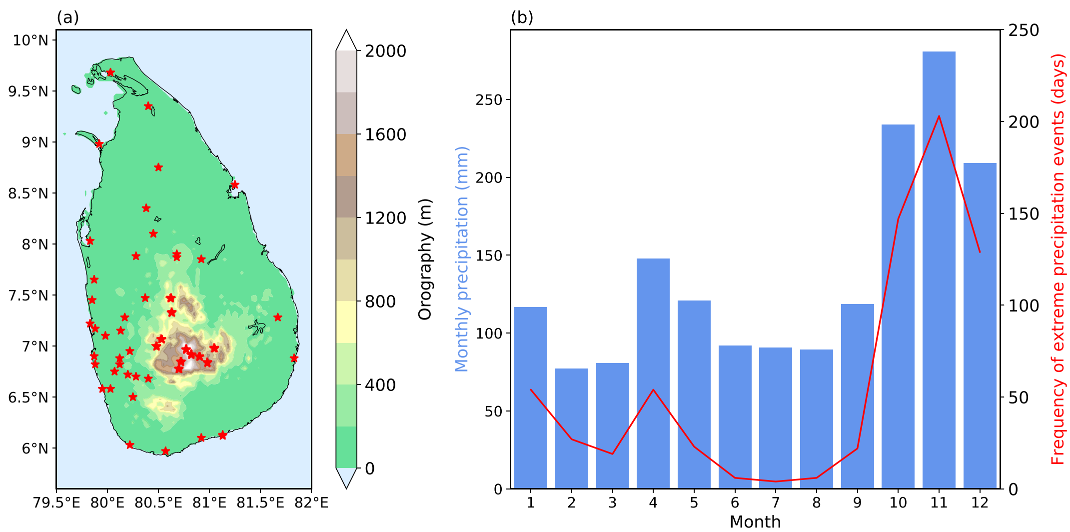

Figure 1. (a) The orography of Sri Lanka (m) obtained from the National Center for Atmospheric Research TerrainBase data set (National Geophysical Data Center, NESDIS, NOAA, U.S. Department of Commerce, 1995). Red stars show locations of 51 meteorological stations that are managed by the Department of Meteorology, Sri Lanka. (b) Monthly precipitation (mm; blue bars) and the frequency of extreme precipitation events (days; solid red curve) in Sri Lanka during January–December 1979–2016, computed using the ERA5 reanalysis data set. Extreme precipitation events are defined as events with area-mean daily rainfall over Sri Lanka exceeding the 95th percentile of daily rainfall on all days in the analysis period.

The data is available from January 1981, and has been used in many previous studies (e.g., Hapuarachchi & Jayawardena, 2015; Jayawardena et al., 2020). The Department of Meteorology, Sri Lanka calculates daily precipitation by summing precipitation between 03 UTC (day 0) and 03 UTC (day +1). Thus, the accumulation period in the two rainfall datasets used in this study has a small difference of 3 hours. Since these stations are not uniformly distributed across Sri Lanka, including being particularly sparse in the north, we interpolate rainfall to a grid using the inverse distance-weighted method. This method is commonly used to estimate rainfall at a given location using observations from nearby meteorological stations (e.g., Chen & Liu, 2012). The unknown rainfall R at the location of interest is estimated as follows:

$$R = \sum_{i=1}^{N} w_{\mathrm{i}} R_{\mathrm{i}} \tag{1}$$

$$w_{\mathrm{i}} = \frac{d_i^{-\alpha}}{\sum_{i=1}^{N} d_i^{-\alpha}} \tag{2}$$

where R_i is rainfall at known meteorological stations, w_i is the weight corresponding to the ith meteorological station, d_i is the distance of the location of interest to each meteorological station, N is the total number of meteorological stations, and α is the power, which we set to two following previous studies (e.g., Chen & Liu, 2012).

Figure S1a in Supporting Information S1 shows a comparison between the station rainfall data set and the ERA5 data set during January–December 1981–2016. The daily mean rainfall over Sri Lanka in the station rainfall data set is more than in ERA5. In fact, the difference is most prominent during the southwest monsoon season (not shown). The two datasets are highly correlated (Pearson correlation coefficient of 0.8) and have a root mean square error of 1.4 mm day^{-1}. We follow the same method discussed in the previous subsection to identify an extreme precipitation event. The threshold value for an extreme precipitation event is 21.2 mm day^{-1}, and extreme precipitation events occurred on 658 of 13,149 days in the analysis period.

2.3. Weather Patterns

We use a data set of 30 weather patterns that were derived by Neal et al. (2020) using 850 hPa winds from ERA-Interim reanalysis. The weather patterns are defined at 12 UTC during January–December 1979–2016,

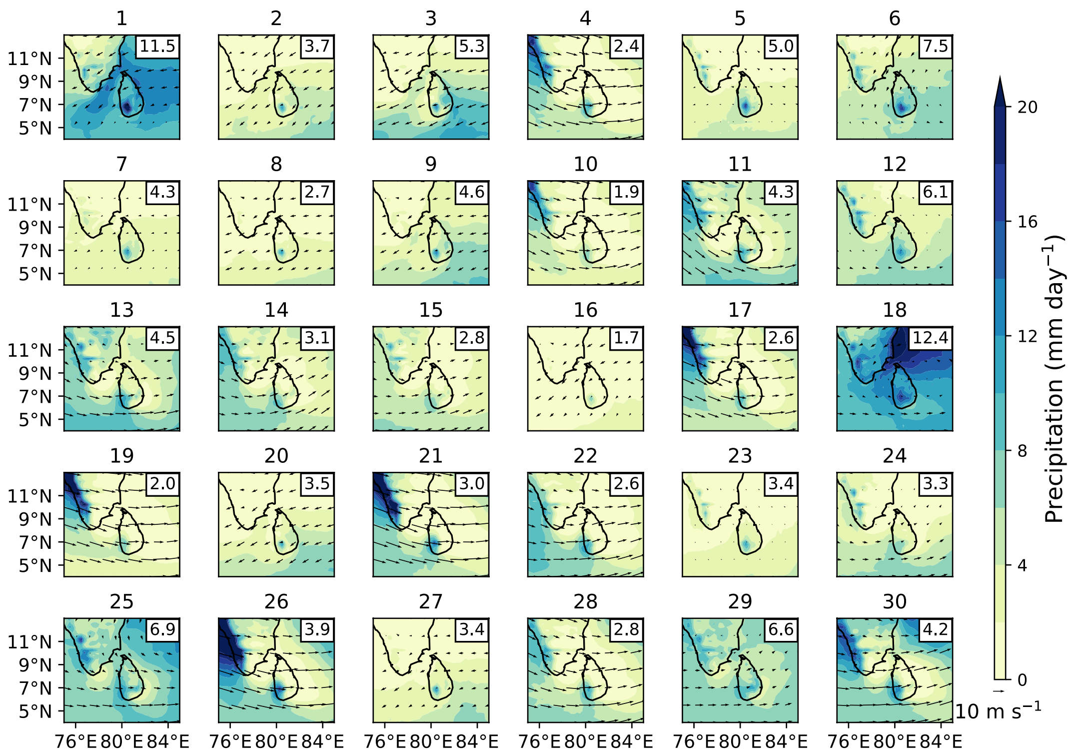

Figure 2. Mean precipitation (shading; mm day^{-1}) from ERA5 in the 30 clusters during January–December 1979–2016. These clusters were originally derived by Neal et al. (2020). Wind vectors show 850 hPa winds from ERA5. Numbers in each subfigure show the mean precipitation over Sri Lanka (mm day^{-1}).

and ordered in an ascending format according to their observed frequencies during the clustering period. On average, each pattern persists for two to three days, following which it transitions into another weather pattern (Neal et al., 2020).

2.4. MJO Index

We use the MJO data set maintained by the Bureau of Meteorology, Australia. The MJO index is based on a pair of combined EOFs of the outgoing longwave radiation data and near-equatorially averaged zonal winds at 850 and 200 hPa (Wheeler & Hendon, 2004). The index has a daily temporal resolution, and is separated into eight phases that represent different geographical locations. From the common period of January–December 1979–2016, only those days on which the amplitude of the index exceeds one standard deviation have been considered (i.e., 8,471 days), in order to identify the MJO phase at a given instant.

3. Results

3.1. Mean Precipitation

Figure 2 shows a composite of mean 850 hPa winds and daily precipitation in the 30 weather patterns (hereafter referred to as clusters) during January–December 1979–2016. The heaviest rainfall in Sri Lanka occurs in cluster 18 in which there is a cyclonic circulation and convergence over the country in the lower troposphere. The western slopes receive approximately 16 mm day^{-1} rainfall, with similar rainfall magnitude off the southeastern coast of India. The second heaviest rainfall occurs in cluster 1, where there are easterly winds of the northeast monsoon over Sri Lanka. The magnitude of rainfall over the western slopes in cluster 1 is more than in cluster 18, whereas northern parts of Sri Lanka receive more rainfall in cluster 18. These two clusters are most common during October–December (see Figure 7 of Neal et al., 2020). For the sake of simplicity, we rename clusters 18 and 1 as *sl-high* and *sl-moderate*, respectively. There are northeasterly winds over Sri Lanka in clusters 2, 3, 8, 9, 20, and 27, but the magnitude of rainfall is much smaller than in the sl-high and sl-moderate clusters (clusters 18 and 1

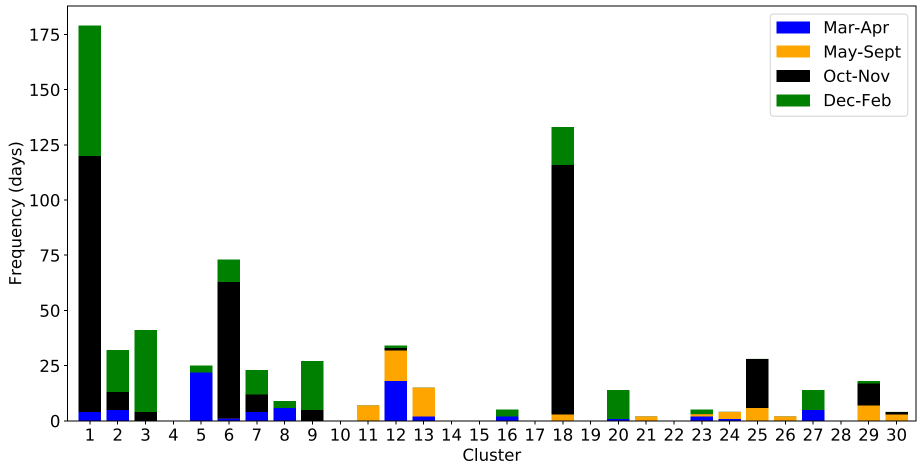

Figure 3. Frequency of extreme precipitation events (days) in Sri Lanka in the 30 clusters during January–December 1979–2016, calculated using the ERA5 precipitation data set. The bars are stacked according to the following four meteorological seasons in Sri Lanka: first intermonsoon (March–April), southwest monsoon (May–September), second intermonsoon (October–November) and northeast monsoon (December–February).

respectively). This is because these clusters are uncommon in November when monthly rainfall over Sri Lanka is the highest. According to Table 2 of Neal et al. (2020), these clusters are most common during December–March or January–May.

The magnitude of precipitation is smallest in cluster 16, which is most common during March. We call this cluster as *sl-light*. This is followed by cluster 10, which is associated with active southwest monsoon conditions over the Himalayan foothills, eastern and northeastern parts of India. The southern coast of India receives a lot more rainfall than Sri Lanka in clusters with westerly winds over Sri Lanka (i.e., clusters 4, 11, 13–15, 17, 19, 21, 22, 25, 26, and 28–30) when moisture flux convergence in the lower troposphere is enhanced. These clusters are mostly associated with the southwest monsoon (swm) season, and in all of them, the western slopes receive more rainfall than other areas of Sri Lanka. We collectively rename these clusters as the *swm* cluster. Clusters 5 and 23, which are associated with the first intermonsoon season, have weak 850 hPa winds. The magnitude of rainfall across most of Sri Lanka is small, but the western slopes receive a lot of rainfall. We collectively rename these two clusters as the *first-intermonsoon* cluster. We get similar results for mean precipitation in the 30 clusters when the station rainfall data set is considered (Figure S1b in Supporting Information S1), indicating the robustness of our results.

3.2. Frequency and Persistence of Extreme Precipitation Events

We now examine the frequency and persistence of extreme precipitation events in the 30 clusters during January–December 1979–2016. This analysis will help in identifying clusters that are most important for disaster management in Sri Lanka. In Figure 3, we group the frequency according to the four meteorological seasons in Sri Lanka. According to Neal et al. (2020), the sl-moderate cluster (cluster 1) is the most common cluster among the 30 clusters. The frequency of extreme precipitation events is the largest in the sl-moderate cluster (179 events), and they are most common during the second intermonsoon season. This is followed by the sl-high cluster (cluster 18; 133 events) and cluster 6 (73 events) in which the highest number of extreme precipitation events also occur during the second intermonsoon season. Interestingly, extreme precipitation events do not occur in most swm clusters (clusters 4, 11, 13–15, 17, 19, 21, 22, 25, 26, and 28–30), and even if they occur (e.g., clusters 11–13, 21, and 24), their frequency in each cluster remains small (<20 days), generally agreeing with Figure 1b.

Compared to the second intermonsoon season, the frequency of extreme precipitation events is much smaller in the first intermonsoon season. Cluster 5 contains the majority of extreme precipitation events that occur during the first intermonsoon season (22 events). The frequency of extreme precipitation events continues to remain the highest in the sl-high cluster (cluster 18) when the station rainfall data set is considered (Figure S2 in Supporting Information S1), suggesting that this result is not sensitive to the choice of precipitation data set. However, unlike

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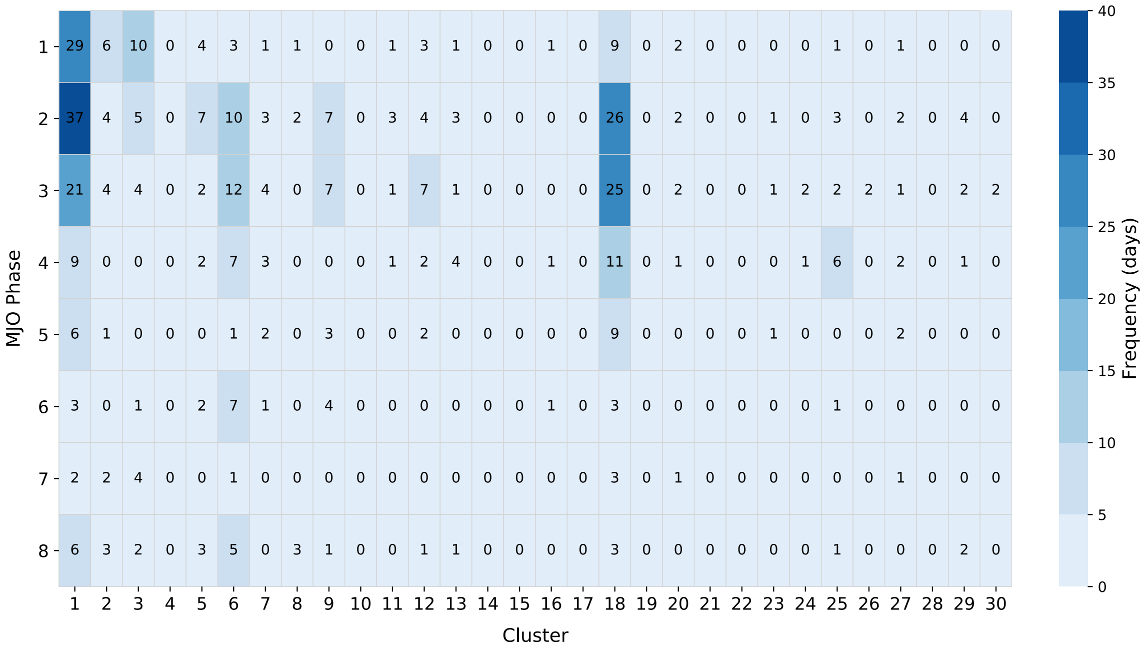

Figure 4. Heatmap showing the frequency of extreme precipitation events (numbers in each grid box; days) in the eight phases of the Madden-Julian Oscillation (MJO) for 30 clusters during January–December 1979–2016. Only those MJO phases when the amplitude exceeds one standard deviation have been retained. The source of precipitation is the ERA5 reanalysis data set.

for ERA5, extreme precipitation events occur in all 30 clusters when the station rainfall data set is considered. In fact, the frequency of extreme precipitation events in the swm cluster (clusters 4, 11, 13–15, 17, 19, 21, 22, 25, 26, and 28–30) increases using the station rainfall data set. This could be related to the larger magnitude of rainfall in this data set than in ERA5 (see Section 2.2). Nevertheless, extreme precipitation events are most frequent in clusters associated with the second intermonsoon and northeast monsoon seasons, and this result is independent of the choice of rainfall data set.

We now centralize the average rainfall over the whole country during each extreme precipitation event to day zero and then compute a lead-lag composite of rainfall from ERA5 (Figure S3 in Supporting Information S1) and the station rainfall data set (Figure S4 in Supporting Information S1) for a period of 3 days that precede and succeed these events. Precipitation recorded during all extreme precipitation events is centered on day zero in the figures. Whilst the frequency of extreme precipitation events is the largest in the sl-high and sl-moderate clusters (clusters 18 and 1 respectively; Figure S3 in Supporting Information S1), the magnitude of extreme precipitation is the largest in cluster 24 (30 mm day^{-1}) and, on average, extreme precipitation occurs a day before and a day after the day-zero event. For the sl-high and sl-moderate clusters, extreme precipitation persists for five consecutive days, whereas for the swm (clusters 4, 11, 13–15, 17, 19, 21, 22, 25, 26, and 28–30) and first-intermonsoon clusters (clusters 5 and 23), it persists for an average of one to two consecutive days. This suggests that the sl-high and sl-moderate clusters and cluster 24 might have a larger potential to cause flooding and other related damage than other clusters. The magnitude of extreme precipitation in these three clusters remains large when the station rainfall data is considered (Figure S4 in Supporting Information S1). Extreme precipitation does not typically occur before and after the day-zero events in most clusters. However, the magnitude of precipitation in many clusters on the preceding and following day of the day-zero event is close to the extreme precipitation threshold.

3.3. Modulation of the Occurrence of Extreme Precipitation by the MJO

We now analyze the modulation of the occurrence of extreme precipitation events by the MJO to determine whether MJO behavior at the large scale adds any predictability to extreme events. Figure 4 shows a heatmap of the frequency of extreme precipitation events in the eight MJO phases for all clusters during January–December 1979–2016.

The frequency of occurrence of extreme precipitation events in most clusters is enhanced in MJO phases 1–4 and suppressed in phases 5–8, in general agreement with previous studies (e.g., Jayawardena et al., 2020). The enhancement of frequency is most prominent in the sl-high and sl-moderate clusters (clusters 18 and 1 respectively), and there is a prominent variation between various clusters. For example, 37 extreme precipitation events occurred in MJO Phase 2 of the sl-moderate cluster as opposed to 0 in the same phase of the sl-light cluster. Thus, only five combinations are responsible for the majority of extreme precipitation events (i.e., MJO phases 1–3 and 2–3 for the sl-moderate (cluster 1) and sl-high clusters (cluster 18), respectively). This result could help meteorologists in developing forecasting products, which could improve planning and disaster preparedness in Sri Lanka. The results are similar when the station rainfall data set is considered (Figure S5 in Supporting Information S1), indicating the robustness of our results.

4. Conclusions

Despite being prone to catastrophic floods and landslides every year, there has been a limited investigation of extreme precipitation events in Sri Lanka. Previous studies mainly focused on analyzing synoptic features during individual heavy rainfall events (e.g., Koralegedara et al., 2019; Warnasooriya et al., 2022) and the role of the Madden-Julian Oscillation (MJO; Jayawardena et al., 2017) in triggering such events. As a result, there has not been any attempt to examine the association of extreme precipitation events with weather patterns in Sri Lanka, which could ultimately help in identifying periods with an increased likelihood of extreme precipitation and floods. In this study, we analyzed the 30 weather patterns derived by Neal et al. (2020) in order to understand their role in causing extreme precipitation events in Sri Lanka during January–December 1979–2016. We also analyzed the modulation of these events by the MJO. We defined extreme precipitation events as those with daily rainfall over Sri Lanka exceeding the 95th percentile of daily rainfall on all days in the analysis period.

We found that the magnitude of rainfall over Sri Lanka was largest (12.4 mm day^{-1}) when there was a cyclonic circulation centered to the east of the country (cluster 18), which caused increased moisture flux convergence in the lower troposphere. This pattern was most common during October–December. In contrast, the magnitude of rainfall was very small in weather patterns associated with the southwest monsoon season (May–September). This is because Sri Lanka receives much less rainfall in this season. The magnitude of rainfall was the smallest in a weather cluster (cluster 16) associated with a weak northeast monsoon circulation over the country during December–February. We hypothesize this to be due to reduced moisture incursion over the country.

We found that extreme precipitation events mostly occurred in clusters associated with the northeast monsoon and second intermonsoon seasons (October–November). They did not occur in clusters associated with the southwest monsoon season when the ERA5 precipitation data set was considered. Furthermore, their frequency during the first intermonsoon season (March–April) was much smaller than during the second intermonsoon season. We then analyzed the persistence of extreme precipitation over Sri Lanka, and found that it persisted for five consecutive days in clusters associated with the largest frequency of extreme precipitation events (i.e., clusters 1 and 18). Its magnitude was the largest in cluster 24.

We finally examined the modulation of the occurrence of extreme precipitation events by the MJO. We found that their frequency was enhanced (suppressed) in phases 1–4 (5–8) of the MJO in general, which was similar to the results of previous studies (e.g., Jayawardena et al., 2020). The impact of the MJO was not prominent in clusters associated with the southwest monsoon season.

In summary, MJO phases 1–4 and clusters 1, 18, and 24 are most important for disaster management in Sri Lanka given the enhanced frequency, intensity and duration of extreme precipitation.

The set of 30 weather patterns used in this study are already being applied to probabilistic medium-range forecasting tools to predict high-impact weather events in India on a trial basis (Neal & Arulalan, 2022; Neal et al., 2022). The results of this study could therefore encourage meteorologists, hydrologists and researchers in developing similar forecasting tools for Sri Lanka in the near future, envisaging improved disaster preparedness. We have shown that the MJO modulates the occurrence of extreme precipitation in various weather patterns. Since the MJO is a prominent source of predictability at long forecast lead times such as the subseasonal-to-seasonal time scales (2 weeks to 2 months), our results could encourage researchers to examine the association between the MJO, weather patterns, and extreme precipitation in Sri Lanka using the subseasonal-to-seasonal prediction models (Vitart et al., 2017). Thus, the results of this study have broad geophysical implications for forecasting extreme precipitation events in Sri Lanka.

A limitation of this study is that despite different climatic regions, we analyzed the mean and extreme precipitation over Sri Lanka as a whole. This might have caused a loss of important fine details related to these different climatic regions. Researchers could therefore analyze the association between weather patterns and extreme precipitation over different climatic regions in a future study.

Data Availability Statement

The ERA5 hourly data on pressure levels is available at https://doi.org/10.24381/cds.bd0915c6. The catalogue of the 30 weather patterns identified by Neal et al. (2020) is available at https://doi.org/10.1594/PANGAEA.902030. The MJO indices from the Bureau of Meteorology, Australia can be accessed at http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt. The Sri Lanka station rainfall data set used for this research is not publicly available due to access constraints imposed by the Department of Meteorology, Sri Lanka. The data set was provided for this work by Dr I. M. Shiromani Priyanthika Jayawardena from the Department of Meteorology, Sri Lanka. It can be requested from the Department's weather and climate data store (http://www.meteo.gov.lk/index.php?option=com_content&view=article&id=100&catid=21&lang=en&Itemid=321) by contacting the Data Processing and Archival Division (metdpa@meteo.gov.lk) or Dr Jayawardena (shirojaya2000@yahoo.com).

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