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Ranking and Characterization of Precipitation Extremes for the past 113 years for Indian western Himalayas

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Abstract

Globally, mountain systems are unevenly exposed to risks of extreme precipitation. Within the Himalayan region, precipitation extremes are a rising concern, but their current understanding is limited. In this study, we use 113 years of precipitation data to rank and characterise precipitation extremes in the Indian Western Himalayas (IWH). Our statistical ranking method integrates precipitation spatial extent and its intensity across different durations for determining the severity of extreme events. The proposed ranking method advances conventional single-day event ranking methods by accounting for multi-day duration to capture persistent precipitation episodes. Results show that the method accurately detects and ranks the most extreme precipitation events that occurred in the IWH and indicate locations of these events. Our results highlight that critical long duration events in the region (e.g. 10 days) are missed at ranks at shorter duration (e.g. 2-3 days), thereby highlighting the importance to multi-day precipitation extremes ranking. In addition, the proposed ranking method provides information with confidence about the event duration that will be associated with the highest impact on society, carrying high significance. Our findings are valuable for flood risk management and disaster risk reduction.

Keywords: Precipitation; Extreme; Multi-day ranking; Western Himalayas; Climate Change, Mountains

1 Introduction

Human-induced global warming is changing the frequency and magnitude of weather-related extremes (Pachauri et al., 2014). In particular, intense precipitation events and associated risks are expected to occur more frequently over Asian regions, especially over India, Bangladesh, and China (Goswami et al., 2006; Parry et al., 2007). Although a uniform and consistent decrease in moderate precipitation has been reported across India (Ghosh et al., 2012), precipitation extremes have changed in a heterogeneous way over India in the past half-century (Rajeevan et al., 2006; Krishnamurti et al., 2013; Guntu et al., 2020). This variability in the occurrences of precipitation extremes in space and time is a consequence of different interacting drivers and complex geographical features (Nicholls et al., 2012).

The Indian Western Himalayan (IWH) region is prone to severe weather conditions due to the joint mechanism of the Indian Summer Monsoon (ISM) and-Western Disturbances (WDs). ISM is usually relevant between June and September (JJAS), and WD is dominant from December to March (DJFM, Krishnan *et al.*, 2019). The climate of the Himalayas is strongly influenced by different types of wind systems, such as mesoscale cyclonic storms, snowstorms, and other high-speed winds along with cloudbursts (Das and Meher, 2019). The combination of these highly energetic phenomena and the pronounced orography often results in sudden precipitation extremes (Nandargi and Dhar, 2011) that cannot be predicted effectively. While daily and sub-daily precipitation extremes usually result in urban and small stream flash flooding, long-duration precipitation episodes can lead to large-scale river floods, inducing major socio-economic impacts (Shukla et al., 2019; Kumari et al., 2019) and other adverse consequences such as deep landslide movements (Ozturk et al., 2018). Precipitation extremes have become a severe concern in recent decades in the IWH region due to higher vulnerability of the society to such events (Das and Meher, 2019).

Several studies have attempted to understand the past changes of extreme precipitation events in the IWH; however, two major gaps remain. Firstly, past assessments are restricted to limited spatial extents often based on a case-by-case approach for a few stations only (Nandargi et al., 2016, Kumari et al., 2019, Priya et al., 2017). Secondly, ranking and characterisation of extreme precipitation events using high-resolution long-term data at high spatial scale are scarce over India, and absent for the IWH region, to the best of our knowledge. To fill these gaps, we analyze the spatio-temporal changes in the precipitation extremes using a high-resolution and long-term dataset. This understanding will be extremely useful to inform disaster management and to develop risk reduction strategies to mitigate adverse impacts. For instance, a simultaneous

increase in magnitude and spatial extent, as shown for river floods in some regions of Europe (Kemter et al., 2020), represents important information for emergency response and disaster recovery. In fact, as the probability of simultaneous events increases it implies that resources and funds need to be provided at many locations at the same time.

Several methods have been proposed in recent years to rank and characterise extremes in different regions of the world. For instance, Müller and Kaspar (2014) developed an 'event-adjusted' method based on the optimization of the event area and the time duration. Ren et al. (2012) presented a similar threshold-based objective method for identification of regional extreme events considering their impact area and duration. Ramos et al. (2014, 2017) developed an objective ranking method to evaluate daily precipitation and multi-day precipitation extremes by taking into account both the area and average intensity of the event. They used a season-dependent definition for extreme events emphasising that these must have large departures from climatology. Beguería et al. (2009) presented a methodology for continuous seasonal mapping of peak intensity, magnitude and duration of extreme precipitation events based on the extreme value theory for a region in the north-eastern Iberian Peninsula. With the aim of quantifying the severity of large-scale flood events, Uhlemann et al. (2010) and Schröter et al. (2015) defined a severity index, which considers both spatial extent and magnitude by integrating the flood-affected river network length with the flood magnitude.

Our study has two main objectives: (i) to understand the seasonal and long-term changes in frequency and magnitude of extreme events over the 113-year period 1901-2013 for IWH; and (ii)-to develop an objective ranking of extreme precipitation episodes for different durations (from 1 to 10 days) for the entire IWH exploiting the long-term, high-resolution precipitation dataset. The study provides important information on the seasonality and long-term trends in the frequency of extreme precipitation events, along with information on the locations of the highest ranked events. Further, the study objectively ranks and characterises the nature of extreme precipitation events for the 113-year period using a statistical approach adapted from Ramos et al. (2014, 2017). It incorporates three matrices, i.e. spatial extent, magnitude, and duration, for ranking the extreme event. The rationale behind this approach is to integrate, besides the event intensity, its spatial extent and duration, as these characteristics can be decisive for the event impact on society (e.g. Uhlemann et al., 2010, Dung et al., 2015). Hence, the highest-ranked events have a large spatial spread and, simultaneously, are characterised by large departures from the local climatology for that time of the year. After combining the

information on magnitude and spatial extent, we examine and include the information on the duration of each event.

2 Study Area

The Himalayan mountain range plays a dominant role in controlling the weather and climate of the Indian subcontinent (Krishnan et al., 2019). As demonstrated by Krishnan et al. (2019) through numerical model simulations, the 'southwest monsoon' will cease to exist if the 'Himalayas' are removed from their current position. The rugged topography enhances heavy rainfall in the river catchments of the Himalayas resulting in hydrometeorological extremes with cascading adverse impacts on humans, their assets and the environment (Pandit, 2013, Priya et al., 2017). Monsoonal rainfall (JJAS) and Western Disturbances (DJF) are two major atmospheric circulation patterns bringing rainfall in IWH, consisting of the three states Jammu & Kashmir (JK), Himachal Pradesh (HP) and Uttarakhand (UK) (Fig. 1a).

[Please insert figure here]

Figure 1: (a) Topography of the Indian Western Himalayas (IWH) consisting of the three states Jammu & Kashmir (JK), Himachal Pradesh (HP) and Uttarakhand (UK), (b) annual frequency and (c) seasonal frequency of occurrence of precipitation-related disasters in the IWH region since 1900 as per EM-DAT data (D. Guha-Sapir et al n.d.,) (d) annual number of deaths in the IWH region due to hydro-climatological hazards as per EM-DAT data.

The IWH region showcases a complex topography with elevation ranging from 184 m in the valleys to 8500 m at mountain peaks (Fig. 1a). The complex topography strongly affects the spatial distribution of rainfall (Joshi and Kumar, 2007; Kumari et al., 2017). Increasingly, extreme weather conditions and natural disasters are becoming common in IWH (Fig. 1b), and in most cases, disasters are triggered by high rainfall events. There is a strong seasonal pattern in the frequency of events (Fig. 1c) with disasters occurring mainly during monsoonal rains and WDs. The frequency of disaster occurrence in the IWH region increased significantly in the 20th century. Moreover, trends in annual losses in terms of the number of deaths shows a remarkable increase after 1990 (Fig. 1d). The extremes and related disasters over these years caused high socioeconomic impacts in terms of casualties, affected people, and economic losses. The observed trend of precipitation extremes has direct implication not only for the

communities in the IWH, but also for water-resource managers and decision makers, as growing risks demand preparedness decisions (Singh et al., 2014).

3 Data and Method

3.1. Precipitation data

We use the high-resolution (0.25°×0.25°) gridded daily rainfall data from the Indian Meteorological Department (IMD) developed by Pai et al. (2014). Given the sparse and uneven distribution of rain gauges in the region, a gap-free, continuous and gridded data was generated using daily rainfall measurements. The station data was converted to gridded data through spatial interpolation by employing the Inverse Distance Weighted scheme. The data is freely available at the archive of the National Data Centre, IMD, Pune (see section data sources) for the period 1901 to 2013.

3.2. Ranking method

It can be rather difficult to evaluate extreme events that cover areas with significant differences in the average precipitation on a daily scale. This difficulty is further compounded by large differences in the variability of the local precipitation. Therefore, the use of daily normalized precipitation anomalies (that take into account the different variability range in each grid point) corresponds to a key step to obtain a meaningful ranking of daily precipitation extremes in the IWH (Ramos et al., 2014). It allows characterizing each day taking into account not only the severity of the precipitation but also the associated spatial extension. To rank precipitation extremes over multi-day accumulated periods, a three-step method is used, following the methodology previously developed Ramos et al. (2017).

Step 1: We use the daily normalized precipitation anomalies ($A_{C,i,j}$) given by

$$A_{C,i,j} = \frac{P_{c,i,j} - \mu_{c,i,j}}{\sigma_{c,i,j}} \qquad (1)$$

where $P_{c,i,j}$ is the precipitation value, $\mu_{c,i,j}$ is the daily Julian mean, and $\sigma_{c,i,j}$ is the daily standard deviation (SD) for a particular year and day (c) and for a particular grid point (i, j). Only days with precipitation above 1 mm (wet days) are taken into account in the computation of the daily climatological series. The daily Julian mean and SD are computed for the entire observational period 1901-2013 (i.e. 113 years). A 7-day running mean is applied afterwards to the

climatological series to smooth the noisy time series. Therefore, for each day and each grid point, a normalised precipitation departure from climatology is computed.

Step 2: We compute the accumulated precipitation anomalies (Eq. 2) for a certain period p over multi-day periods (n).

$$AA_{C,i,j} = \sum_{c=1}^{n} A_{C,i,j} \qquad (2)$$

The 3-day accumulated precipitation anomaly, for example, on 5 September 1995 corresponds to the sum of the normalized precipitation anomalies relative to 3-5 September 1995.

Step 3: The final step computes the magnitude of the precipitation extreme for each accumulated precipitation anomaly period. We have adopted the procedure proposed by Ramos et al. (2014). The magnitude of extreme events is given on a daily basis by an index that is obtained after multiplying two values:

- the area (**A**, in percentage of IWH) that has precipitation anomalies (at each time scale) above 2 standard deviations SD, and
- the mean value of these anomalies (**M**) for all the grid points that are characterized by precipitation anomalies above 2SD.

So, for single-day ranking, the magnitude ($\mathbf{R_d}$) is calculated using a single-day anomaly ($A_{c,i,j}$) and for multi-day rankings, the magnitude ($\mathbf{R_m}$) is computed using the accumulated anomaly ($AA_{c,i,j}$) for that day over all grid points. The 2SD threshold corresponds roughly to the 95% percentile of the daily precipitation distribution at each grid point. However, the methodology can be easily adapted, for instance, by increasing the SD threshold when particularly extreme events are of interest.

3.3 Selection of critical duration of extreme event ranking

Theoretically, the ranking method can be applied to any event duration. To obtain sensible values for the duration of extreme precipitation events in the IWH, we compute the critical event duration. We define this value as the duration beyond which the mean ranking magnitude of extremes (R) remains constant with increasing duration. The mean magnitude of the top 5, 20, and 100 events increases with event duration and levels off between 5 and 10 days (Fig. 2). This agrees with the observation that, for the IWH region, an event lasting longer than 10 days

is practically not possible. Thus, we compute 1-day and multi-day rankings up to 10 days. For brevity, we report the results for 1-, 3-, 5-, 7- and 10-day precipitation rankings.

[Please insert figure here]

Figure 2: Magnitude (R_m) for the first 5, 20 and 100 highest ranked events at various multi-day duration of accumulated precipitation. X-axis denotes duration (i.e. time period) of an event in days. Y-axis denotes the mean magnitude of the event in mm.

4 Results and Discussion

Section 4.1 reports the seasonal and long-term (113 years) evolution of the magnitude and frequency of extremes at different duration. Section 4.2 presents the results of the ranking for IWH and discusses specific events. The ranking of extreme events is based on the magnitude R that incorporates both percentage area (A, spatial extension) and mean value (intensity of extreme precipitation) for different durations. Finally, we shed light on the major limitation of our approach by discussing specific missed cases in the ranking (Section 4.3).

4.1 Seasonal and long-term evolution of precipitation extremes

Fig. 3 (a&b) shows the decadal progression of frequency and mean magnitude (R) of the extremes in IWH for different durations. There is a sharp increase in both frequency and magnitude of extreme precipitation in the last three decades. This pattern is in congruence with EM-DAT data (Figure 1b) confirming an increase in disasters in the Indian Western Himalayan and also validating our findings. There is also a pronounced seasonal pattern, similar for all durations, in the occurrence (Fig. 3c) and magnitude (Fig. 3d) of the top 1% events. In both cases, the maxima occurs around August/September and a less pronounced secondary maximum is visible in February. This pattern is explained by the two major atmospheric patterns that are responsible for precipitation over IWH, i.e. ISM from June to September, and WD dominating from December to March. Interestingly, the frequency of extremes increases strongly with duration during ISM (Fig. 3c). These results highlight that, similar to other parts of the world (Marelle *et al.*, 2018), precipitation extremes in IWH have a clear seasonal pattern, which might be changed due to climate warming. Although outside the scope of this study, an assessment of seasonal changes in the occurrence of extremes in IWH is worth considering in future studies.

[Please insert figure here]

Figure 3: Distribution of precipitation extremes over IWH. Decadal distribution of (a) frequency, and (b) mean magnitude of top 1% extreme events for different durations. Monthly distribution of (c) frequency (d) and magnitude of top 1% extreme events for different durations.

4.2 Ranking of extreme events

In this section, we present results for 1-day, 3-days, 5-days, 7-days and 10-days extreme precipitation events ranking in the IWH. Results obtained for the top 10 events are sown in SI Table 1 and Fig. 4. Interestingly, many events are not independent and they overlap at different durations, as we can observe there are only 15 (out of 50) unique events. Furthermore, it is clear from Fig. 4 that the different top 10 ranks are dominated by four events that occurred respectively in September 1995 (green bars), March 1990 (red bars), September 1988 (white bars), July 1995 (light blue bars).

[Please insert figure here]

Figure 4: Magnitude (R_m) and rank for the top 10 events at different durations (1, 3, 5, 7, and 10 days) of accumulated precipitation. Arrowhead indicates the direction of increasing values.

In particular, the September 1995 and March 1990 events dominate the top 10 ranks with 15 and 13 top ranks, respectively. This dominance exerted by just a few extreme precipitation episodes is expected to occur at longer durations, since we analyse successive accumulated precipitation days over relatively long periods. Therefore, 2 or 3 intense precipitation anomalous days will be sufficient to influence successive periods. In the next subsection, we present specific cases demonstrating the potential of a single day and multi-day duration extreme event ranking over IWH.

4.2.1 Single-day extreme ranking

The 1-day first rank event on 02-08-1997 (Fig. 5a) was widespread, with 49% of IWH showing precipitation anomalies larger than 2 SD. It reached a magnitude of ~10 SD (Fig. 5b). The event hit the north-eastern section of IWH, with maximum precipitation of 235mm and with precipitation above 200mm observed at several grid points.

[Please insert figure here]

Figure 5: (a) Spatial distribution of accumulated precipitation (mm) and corresponding standard deviation anomalies (black contour) of a 1-day precipitation event occurring on 02-08-1997. (b) Spatial coverage and magnitude of the extreme event occurring between 31-07-1997 and 05-08-1997. Area means percentage of IWH with precipitation anomalies above 2 SD, magnitude is the mean of anomalies above 2 SD.

The same event is also present in the 3-days ranking (rank 2 & 10) underlining that it was dominant at the daily scale, but precipitation on the day before and the day after were also relevant (Fig. 5b). In this regard, any ranking methodology focussing on single-day duration (often used in the literature) would be limited in capturing its evolution. The absence of this event from further multi-days ranking (5-, 7-, and 10-days ranking) shows that the extreme event occurred only for 3-4 continuous days (i.e. 1-4 August). This event occurred prior to a highly localised cloud bursting event over Chiragaon village in Shimla district of Himachal Pradesh between 8-14 August 1997 resulting in 135 fatalities along with 20 injuries (Source EM-DAT data; Yogendra, 1999; Pathania, 1997). Interestingly, the precipitation between 8-14 August 1997 was not extreme and hence did not show up in the top 10 ranking. Thus, it is likely that the extreme precipitation on 1-4 August increased the river flow and decreased the capacity of the soil to absorb further rainfall in the following days. This might have strongly increased the vulnerability to landslides during the subsequent cloud bursting event.

The rank 2 event (Fig. S1) of 1-day ranking on 05-09-1995 covered a wider area when compared to the top event, affecting an area of 66% of IWH (>2SD), but with a lower overall intensity with a mean anomaly value ~6 SD. The precipitation over some localised grid cells surpassed 300mm, with a maximum value of 425mm (Fig. S1). Most of IWH received rainfall above 150mm. This event is also present at 3-, 5-, 7-and 10-days ranking. This clearly indicates that it is a continuous extreme event expanding over multi-days (at least up to 10 days) and affecting major easterly portions of JK, HP and northwestern portions of UK. The rank 3 event (Fig. S2) of 1-day ranking took place on 09-02-2010 affecting 85% of IWH area (> 2 SD), albeit with comparatively lower intensity ~5 SD. This event is absent at 3-, 5-, 7-, and 10-days rankings revealing that it was a single day extreme event. The precipitation on this day attained a maximum value of 127mm. Nevertheless, this event was clearly linked with a landslide causing 17 deaths in Hatia Bala town of JK (Source EM-DAT data; Konagai and Sattar, 2012).

Based on these results, we can re-iterate that the ranking method is highly dependent on combined indices values that take into account simultaneously the magnitude of the event as well as the total area affected. This method is certainly more effective than a single metric of spatial spread or intensity at a single day duration.

4.2.2 Multi-day extreme ranking

Several events, which are not significant on a daily ranking, become significant, based on intensity and spatial extension at longer time durations. For instance, four events appear in the 3-day ranking category (rank 3, 6, 7 & 9) that are absent in the 1-day ranking. The changes in the ranking of different duration highlight the importance of multi-day ranking of extremes, as it is crucial to capture events of varying spatiotemporal characteristics. The extreme event of 05-09-1995 accounts for 15 occurrences (green bars in Figure 4). Below, we provide a more detailed description of the spatio-temporal progression of the event at short (3-day) and long (10-day) duration.

Event of 05-09-1995 in short and long duration

Figure 6 (Panel I) shows the cumulative rainfall for the short duration time scales of this event, for which it is ranked first. The short duration event affected an area of 69% of IWH (>2SD) with a mean anomaly value of ~12.4 SD.

[Please insert figure here]

Figure 6: Panel I- Spatial distribution of accumulated precipitation (mm) and corresponding standard deviation anomalies (black contour) of the 3-days precipitation event on 05-09-1995 i.e. from 03-09-1995 to 05-09-1995. Panel II (a-j)- Spatial distribution of daily precipitation (mm) and corresponding standard deviation anomalies (black contour) of the 10-days period spanning between 28-08-1995 and 06-09-1995. (k) Spatial coverage and magnitude of the extreme event.

The event was not a short-lived one and lasted for a considerable longer duration of 10-days from 28 Aug – 6 Sept 1995 (Fig. 6 (Panel II)). Daily precipitation anomalies higher than 2 SD are present on all the days except 28-08-1995 (Fig. 6k (Panel II))). Precipitation was localised and less intense in the first four days (Fig. 6 part II (a-d)). Afterwards it intensified and became widespread, attaining its peak on 5 September. As reported by Vellore et al. (2016), two storms hit IWH during these 10 days. The first storm was active on the first four days, while the second

storm struck during the last six days (Vellore et al., 2016), as can be concluded from Fig. 6 (Panel II).

- For the first four days, the highest values of precipitation can be observed over an NW-SE band of IWH affecting mainly HP and the UK. Precipitation during these four days was relatively scattered and less intense (Fig.6 Panel II (a-d)).
- On the first day, i.e., 28-08-1995, no area got affected above anomaly of 2 SD, and max precipitation was only up to 41mm. Whereas, on the second and third day affected 2% and 6% of the IWH area above anomaly of 2 SD and M value on these two days were equal to 2.9 SD with max precipitation of 67mm and 79mm. Anomalies up to 4 SD were seen on these two days in regions of the UK.
- On the fourth day, i.e. 31-08-1995 (Fig. 6, Panel II d), this particular pattern of precipitation receded affecting 2% of area above anomaly benchmark and with a mean intensity of 3 SD, with precipitation being mainly localised over the lower southernmost part of the UK with anomalies value over grids up to 4 SD and max precipitation up to 87mm.
- Onward, the fifth day we see precipitation in an entirely NE-SW orientation, i.e. almost orthogonal to the previous one, affecting mainly the eastern portion of JK. This storm affected on its first day (1 September) an area of 13% of IWH (>2 SD) with mean anomaly value of 3 SD and reaching 4 SD locally. This NE-SW precipitation band increased in both magnitude and area affected until 5 September (Fig. 6, Panel II i).

This prolonged event was related to the disastrous floods that took place in HP, JK and almost the entire northern India (Haryana, Delhi, Punjab, Bihar, Uttar Pradesh) between Sept 1 – Sept 20 causing the death of 1479 people and affecting 32.704.000 people in total (https://public.emdat.be/data;Blaskovic, 2018; Sen, 1995).

4.3 Strengths and limitations of the ranking approach

To demonstrate the strengths and limitations of our approach, we present two particular events that are only included at multi-day ranking. Additionally, we discuss why this approach fails to assign a top rank to the event on 17 June 2013 that triggered the deadliest disaster in Uttarakhand.

4.3.1 Strengths: Capturing disastrous events at multi-day time scales

Case I: 12th July 1993 event

The extreme event on 12-07-1993 (orange bar in Fig. 4) had tremendous socioeconomic impacts as it heavily flooded the HP and JK states as well as other northwestern states (Punjab, Haryana, Gujarat, Rajasthan, Chandigarh) of India causing a death toll of 827 and affecting 128 million people (Source: EM-DAT data). The event appears only in the 5-days ranking at the 6th rank, with indices A and M as 82% and 10.5 SD, respectively. Not all five accumulating days of this event were severe enough to be included in top 10 of the daily ranking (Fig. 7a). An assessment of the atmospheric circulation at the synoptic scale by Kulkarni et al. (1995) showed the combined effect of meteorological configurations responsible for the event. It was caused mainly due to (i) a well-marked low-pressure system over the region, (ii) a cyclonic circulation that extended up to mid-tropospheric levels and prevailed over the regions between 9 and 10 July, (iii) an off-shore trough running from the north Maharashtra coast to the Kerala coast, persisting during the four days between 9-12 July, and (iv) a western disturbance that lay over north Pakistan and its neighbourhood on 9 July, and moved away from north-eastward across Jammu and Kashmir on 14 July (Kulkarni et al., 1995).

[Please insert figure here]

Figure 7: Daily evolution of the spatial coverage and magnitude of the extreme events on 12-07-1993 (a) and 22-03-1990 (b).

Case II: 22nd March 1990 event

The event on 22-03-1990 is linked with massive flooding of JK (Kaluchak, Kargil) over the two days 21-22 March 1990, causing 69 fatalities. This event is at rank 7 in 3-days ranking (red bar in Fig. 4) but not in the top 10 of the daily ranking (Table 1). However, unlike the previous case (which was captured only once at 5-day duration), this event is among the top 10 ranks for all other durations and occupies 13 out of 50 ranks (Table 1). This is an interesting finding for an event that remains unnoticed at 1-day scale. Its precipitation is relatively less intense and localised on the first three days compared to other days where it intensified and became more widespread (Fig. 7b).

4.3.2. Limitation: Why is the deadliest 17th June 2013 Uttarakhand disaster not present in the top 10 extreme events?

In June 2013, Uttarakhand state experienced an extreme 4-day rainfall event leading to devastating floods and landslides. During the event, 370 mm/day of rain was recorded at Dehradun corresponding to 27% of the annual rainfall (Gosain et al., 2015). Heavy rainfall caused a breach in a moraine dammed lake, leading to severe flooding that resulted in the loss of thousands of lives, and massive infrastructure damage that affected 4200 villages, 1636 roads, 144 bridges, and 19 hydropower plants (Das, 2013, Rautela, 2013, Dube et al., 2014, Kala, 2014, Gosain et al., 2016). This event is considered as India's worst natural disaster since the December 2004 Indian Ocean tsunami (Dubey et al., 2013;Kumari *et al.*, 2019). Reconstruction cost after the disaster is estimated to be almost 480 million pounds (Jogesh et al 2016; Kumari *et al.*, 2019). We analysed the data from 14 to 17th June 2013 to understand why the deadliest disaster in Uttarakhand is missing from the top 10 ranks for the 1-day and multi-day extremes. 17th June was the most extreme day of this event (mean magnitude M = 225 mm; rank 38), followed by 16 June (M = 156 mm; rank 96). We compared these events with the 1-day top 1 event of 02-08-1997 and the top 3 event of 09-02-2010 (Table 2, Fig. 8). Although day 17-06-2013 holds a mean magnitude of 8.3 SD, it is a localised event affecting only 27% of the IWH area. Day 16-06-2013 is more widespread, affecting 40%, but considerably less intense with a mean magnitude of 3.4 SD. In comparison, the rank 1 event on 02-08-1997 (Fig. 8d) affected almost half the area of IWH with a high intensity (M = 9.9 SD). Likewise, the rank 3 event on 09-02-2010 (fig. 8c) had an even larger spatial spread (A = 85%), albeit a lower intensity of 4.4 SD. Besides, the intensity of Uttarakhand disaster accumulating days was localised with some specific regions receiving extremely high rainfall in comparison to others. Hence, the mean value of intensity did not reach high value because of the small spatial extent of the event. The high intensity, but low affected area represent important characteristics of this event and are compatible with the disaster-affected communities, as most of them were concentrated in the Mandakini catchment (Kedarnath valley in Uttarakhand state of IWH) and surrounding regions (India Disaster Report 2013). Our results agree with Mishra and Srinivasan (2013) who highlighted that rainfall during the Uttarakhand floods was not the most intense rainfall this region has ever faced, however, it was considered one of India's worst disasters due to the subsequent impact on society.

We would also like to reiterate that not all extreme precipitation events are associated with geomorphological disasters with significant human and socioeconomic impacts. Some disasters, such as the Uttarakhand 2013 event, result from a number of contributing factors and the relation between precipitation and impact is typically nonlinear (e.g. Kreibich *et al.*, 2017). Natural hazards are transformed into disasters due to socioeconomic factors, such as rising population, poorly regulated tourism industry, and poor infrastructure development including road network

expansion in environmentally sensitive zones (Ziegler et al., 2014; Bhambri et al., 2016). Extreme events have occurred in Uttarakhand previously (Dimri, 2013). But the large number of human casualties and the massive damage observed in the June 2013 extreme event can be broadly attributed to two additional reasons: (1) coincidence of the annual pilgrimage with the event exposing a large number of people to the hazard, and (2) heavy rainfall on the preceding days of June 10 and 11, 2013 that saturated the soil and made the ground vulnerable to landsliding. Furthermore various other anthropogenic factors, such as unchecked and rapid land-use changes and urban infrastructure development, enhanced the intensity and scale of the impact (Kala, 2014). Finally, the Indian monsoon system reached the region two weeks earlier than normal in June 2013 (Joseph et al., 2015) and hence, the region was not prepared for that. Therefore, the compounding effect of various factors in combination with the relatively high precipitation values caused disastrous impacts (Sharma et al., 2013).

[Please insert figure here]

Figure 8: Spatial distribution of accumulated precipitation (mm) and corresponding standard deviation anomalies (black contour) during the Uttarakhand 2013 disaster and the top-ranked event at 1-day. (a-b) represent days during Uttarakhand floods, (c) and (d) are the rank 3 and rank 1 event, respectively.

Overall our results highlight that the developed ranking scheme is not biased to extreme events that affect small areas only even when these t can impinge catastrophic impacts at a more local scale. The method was developed to consider both the level of spatial-spread (metric A), as well as the intensity of the event (metric M) in the affected area. Both metrics are essential to calculate a representative ranking magnitude, which is the basis of comparison of different precipitation events. The case studies in sections 4.3.1 and 4.3.2 highlight that there is a further need to reduce the spatial scale of a domain to state or even basin to obtain a more extensive analysis of extreme precipitation events for that smaller spatial scale, but that are relevant to shape effective disaster and hydrological policies there.

5 Conclusions

We ranked extreme precipitation events in Indian Western Himalayan (IWH) accounting for precipitation magnitude and spatial extent at different duration. Events are ranked higher due to particularly high precipitation magnitudes, whereas other events are characterized by

extensive spatial spread or due to persistent rainy conditions for a longer duration. We observe that the ranking method apart from identifying such long-duration extremes are also useful in determining the timing of the maximum impact. Our analysis reveals the benefits of using a multi-day ranking scheme to better quantify and track the spatial and temporal propagation of the extreme. The different rankings databases obtained considering the various durations are useful for other studies focused on the impacts of extreme precipitation periods covering relatively large areas, but also useful for studies assessing the evolution of the atmospheric circulation during those days.

Future studies can link the analysis of extremes with associated socio-economic impacts. One way to do this is to add a fourth metric of population exposed to the extremes, thereby giving a higher rank to the events that occur in densely populated areas. As per the results of present study, it is true that there is not any direct relation between the positions of events in the table and the socioeconomic impacts as there are a number of other factors responsible. But our approach indeed determines that if we keep all other varying factors constant then the probability of the socioeconomic effects are well correlated with the ranking position. Our classification scheme is also useful, as shown in several case studies, to determine which time scale is more likely to bring socioeconomic impacts. In many cases, socioeconomic impacts are not just a result of short and intense events but also accumulated moderate events for a more extended period, which then become significant.

Acknowledgement

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Competing interest

The authors declare no conflict of interest.

References

Beguería, S., Vicente-Serrano, S.M., López-Moreno, J.I., García-Ruiz, J.M., 2009. Annual and seasonal mapping of peak intensity, magnitude and duration of extreme precipitation events across a climatic gradient, northeast Spain. Int. J. Climatol. 29, 1759–1779. https://doi.org/10.1002/joc.1808

Blaskovic, T., 2018. Worst floods since 1995 hit Himachal Pradesh, India.

Das, L., Meher, J.K., 2019. Drivers of climate over the Western Himalayan region of India: A review. Earth-Sci. Rev. 198, 102935. https://doi.org/10.1016/j.earscirev.2019.102935

D.Guha-Sapir, D. EM-DAT: The Emergency Events Database. Available online: www.emdat.be (accessed on 20 August 2020)

Dung, N. V., Merz, B., Bárdossy, A., & Apel, H. (2015). Handling uncertainty in bivariate quantile estimation - An application to flood hazard analysis in the Mekong Delta. Journal of Hydrology, 527, 704-717. doi:10.1016/j.jhydrol.2015.05.033

Ghosh, S., Das, D., Kao, S.-C., Ganguly, A.R., 2012. Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes. Nat. Clim. Change 2, 86–91. https://doi.org/10.1038/nclimate1327

Guntu, R.K., Maheswaran, R., Agarwal, A., Singh, V.P., 2020. Accounting for temporal variability for improved precipitation regionalization based on self-organizing map coupled with information theory. J. Hydrol. 590, 125236. https://doi.org/10.1016/j.jhydrol.2020.125236

Kahlon et al, 2014. Landslides in Himalyan Mountains: A study of Himachal Pradesh, India. International Journal of IT, Engineering and Applied Sciences Research (IJIEASR) I 3, 28–34.

Konagai, K., Sattar, A., 2012. Partial breaching of Hattian Bala Landslide Dam formed in the 8th October 2005 Kashmir Earthquake, Pakistan. Landslides 9, 1–11. https://doi.org/10.1007/s10346-011-0280-x

Krishnamurti, T.N., Martin, A., Krishnamurti, R., Simon, A., Thomas, A., Kumar, V., 2013. Impacts of enhanced CCN on the organization of convection and recent reduced counts of monsoon depressions. Clim. Dyn. 41, 117–134. https://doi.org/10.1007/s00382-012-1638-z

Krishnan, R., Shrestha, Arun B., Ren, G., Rajbhandari, R., Saeed, S., Sanjay, J., Syed, Md.A., Vellore, R., Xu, Y., You, Q., Ren, Y., 2019. Unravelling Climate Change in the Hindu Kush Himalaya: Rapid Warming in the Mountains and Increasing Extremes, in: Wester, P., Mishra, A., Mukherji, A., Shrestha, Arun Bhakta (Eds.), The Hindu Kush Himalaya Assessment. Springer International Publishing, Cham, pp. 57–97. https://doi.org/10.1007/978-3-319-92288-1_3

Kulkarni et al, 1995. ANALYSIS OF SEVERE RAINSTORMS OVER GUJARAT AND PUNJAB DURING THE 1993 MONSOON.

Kumari, S., Haustein, K., Javid, H., Burton, C., Allen, M.R., Paltan, H., Dadson, S., Otto, F.E.L., 2019. Return period of extreme rainfall substantially decreases under 1.5 °C and 2.0 °C warming: a case study for Uttarakhand, India. Environ. Res. Lett. 14, 044033. https://doi.org/10.1088/1748-9326/ab0bce

Kreibich, H., Di Baldassarre, G., Vorogushyn, S., Aerts, J. C. J. H., Apel, H., Aronica, G. T., . . . Merz, B. (2017). Adaptation to flood risk: Results of international paired flood event studies. Earth's Future, 5(10), 953-965. doi:10.1002/2017ef000606

Krishnan R, Sabin TP, Madhura RK, Vellore RK, Mujumdar M, Sanjay J, Nayak S, Rajeevan M. 2019. Non-monsoonal precipitation response over the Western Himalayas to climate change. Climate Dynamics, 52(7–8): 4091–4109. https://doi.org/10.1007/s00382-018-4357-2.

Müller, M., Kaspar, M., 2014. Event-adjusted evaluation of weather and climate extremes. Nat. Hazards Earth Syst. Sci. 14, 473–483. https://doi.org/10.5194/nhess-14-473-2014

Marelle L, Myhre G, Hodnebrog Ø, Sillmann J, Samset BH. 2018. The Changing Seasonality of Extreme Daily Precipitation. Geophysical Research Letters, 45(20). https://doi.org/10.1029/2018GL079567.

Nandargi, S., Dhar, O.N., 2011. Extreme rainfall events over the Himalayas between 1871 and 2007. Hydrol. Sci. J. 56, 930–945. https://doi.org/10.1080/02626667.2011.595373

Nandargi, S., Gaur, A., Mulye, S.S., 2016. Hydrological analysis of extreme rainfall events and severe rainstorms over Uttarakhand, India. Hydrol. Sci. J. 61, 2145–2163.

https://doi.org/10.1080/02626667.2015.1085990

Natural Disaster Management, n.d.

N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang, 2012: Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

Ozturk, U., Marwan, N., Korup, O., Saito, H., Agarwal, A., Grossman, M.J., Zaiki, M., Kurths, J., 2018. Complex networks for tracking extreme rainfall during typhoons. Chaos Interdiscip. J. Nonlinear Sci. 28, 075301. https://doi.org/10.1063/1.5004480

Pahauri et al, 2014. Climate Change 2014: Synthesis Report.

Pai, D.S., Sridhar, L., Rajeevan, M., Sreejith, O., Satbhai, N., Mukhopadhay, N., 2014. Development of a new high spatial resolution (0.25° × 0.25°) Long Period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region.

Pandit, M.K., 2013. The Himalayas must be protected. Nature 501, 283–283. https://doi.org/10.1038/501283a

Parry et al, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability.

Pathania, K., 1997. At least 140 killed in floods in northern India.

Priya, P., Krishnan, R., Mujumdar, M., Houze, R.A., 2017. Changing monsoon and midlatitude circulation interactions over the Western Himalayas and possible links to occurrences of extreme precipitation. Clim. Dyn. 49, 2351–2364. https://doi.org/10.1007/s00382-016-3458-z

Rajeevan et al, 2006. A High Resolution Daily Gridded Rainfall Data for the Indian Region: Analysis of break and active monsoon spells. Curr Sci 91.

Ramos, A.M., Trigo, R.M., Liberato, M.L.R., 2017. Ranking of multi-day extreme precipitation events over the Iberian Peninsula: MULTI-DAY EXTREME PRECIPITATION EVENTS IBERIAN PENINSULA. Int. J. Climatol. 37, 607–620. https://doi.org/10.1002/joc.4726

Ramos, A.M., Trigo, R.M., Liberato, M.L.R., 2014. A ranking of high-resolution daily precipitation extreme events for the Iberian Peninsula: Ranking of the Iberian Peninsula daily precipitation. Atmospheric Sci. Lett. n/a-n/a. https://doi.org/10.1002/asl2.507

Ren, F., Cui, D., Gong, Z., Wang, Y., Zou, X., Li, Y., Wang, S., Wang, X., 2012. An Objective Identification Technique for Regional Extreme Events. J. Clim. 25, 7015–7027. https://doi.org/10.1175/JCLI-D-11-00489.1

Sen, A., 1995. Poor drainage, inept river management, heavy rains lead to one of north India's worst floods.

Shukla, R., Agarwal, A., Gornott, C., Sachdeva, K., Joshi, P.K., 2019a. Farmer typology to understand differentiated climate change adaptation in Himalaya. Sci. Rep. 9, 20375. https://doi.org/10.1038/s41598-019-56931-9

Shukla, R., Agarwal, A., Sachdeva, K., Kurths, J., Joshi, P.K., 2019b. Climate change perception: an analysis of climate change and risk perceptions among farmer types of Indian Western Himalayas. Clim. Change 152, 103–119. https://doi.org/10.1007/s10584-018-2314-z

Satendra, K. J. Anandha Kumar, V. K. Naik, 2014. INDIA DISASTER REPORT 2013. National Institute of Disaster Management.

Uhlemann, S., Thieken, A. H., & Merz, B. (2010). A consistent set of trans-basin floods in Germany between 1952–2002. Hydrology and Earth System Sciences, 14(7), 1277-1295. doi:10.5194/hess-14-1277-2010

Vellore, R.K., Kaplan, M.L., Krishnan, R., Lewis, J.M., Sabade, S., Deshpande, N., Singh, B.B., Madhura, R.K., Rama Rao, M.V.S., 2016. Monsoon-extratropical circulation interactions in Himalayan extreme rainfall. Clim. Dyn. 46, 3517–3546. https://doi.org/10.1007/s00382-015-2784-x

Yogendra, K., 1999. Can flash floods be prevented in HP?

Zolina, O., Simmer, C., Belyaev, K., Gulev, S.K., Koltermann, P., 2013. Changes in the Duration of European Wet and Dry Spells during the Last 60 Years. J. Clim. 26, 2022–2047. https://doi.org/10.1175/JCLI-D-11-00498.1

Supplementary Information

Fig. S1

[Please insert figure here]

Figure S1: Spatial distribution and precipitation intensity of a particular event occurred on 05-09-1995.

[Please insert figure here]

Figure S2: Spatial distribution and precipitation intensity of a particular precipitation event occurred on 09-02-2010.

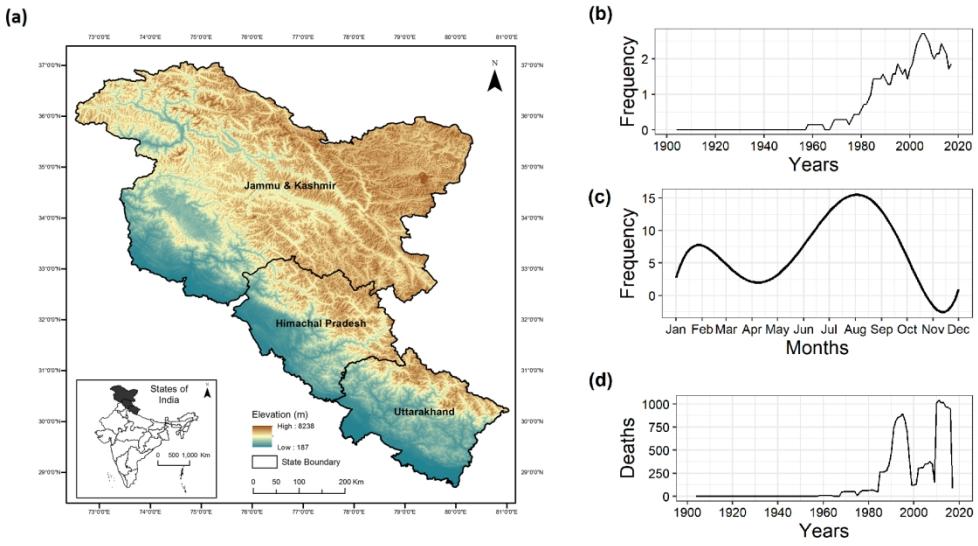

Figure 1: (a) Topography of the Indian Western Himalayas (IWH) consisting of the three states Jammu & Kashmir (JK), Himachal Pradesh (HP) and Uttarakhand (UK), (b) annual frequency and (c) seasonal frequency of occurrence of precipitation-related disasters in the IWH region since 1900 as per EM-DAT data (D. Guha-Sapir et al n.d.,) (d) annual number of deaths in the IWH region due to hydro-climatological hazards as per EM-DAT data.

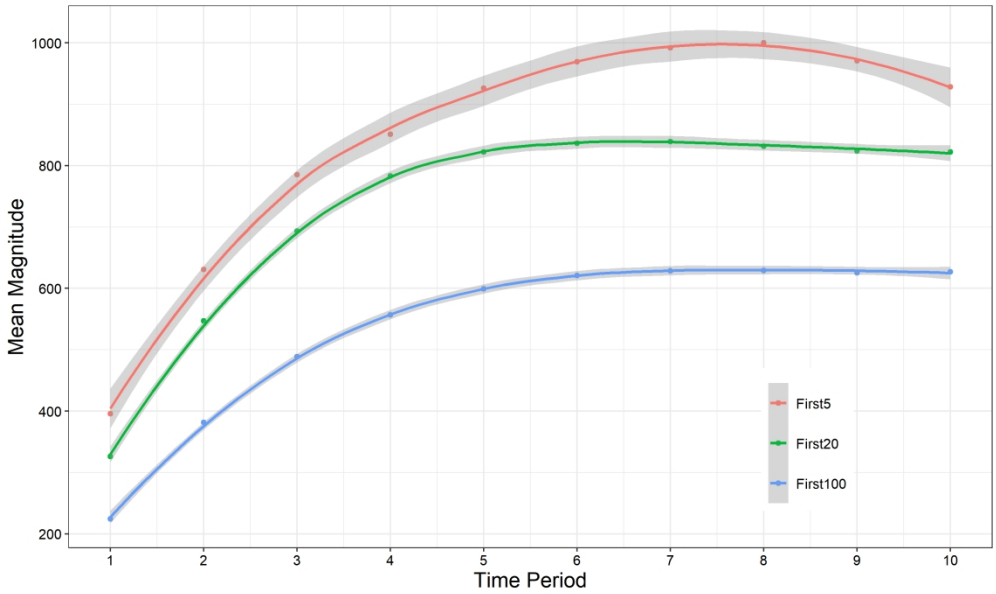

Figure 2: Magnitude (Rm) for the first 5, 20 and 100 highest ranked events at various multi-day duration of accumulated precipitation. X-axis denotes duration (i.e. time period) of an event in days. Y-axis denotes the mean magnitude of the event in mm.

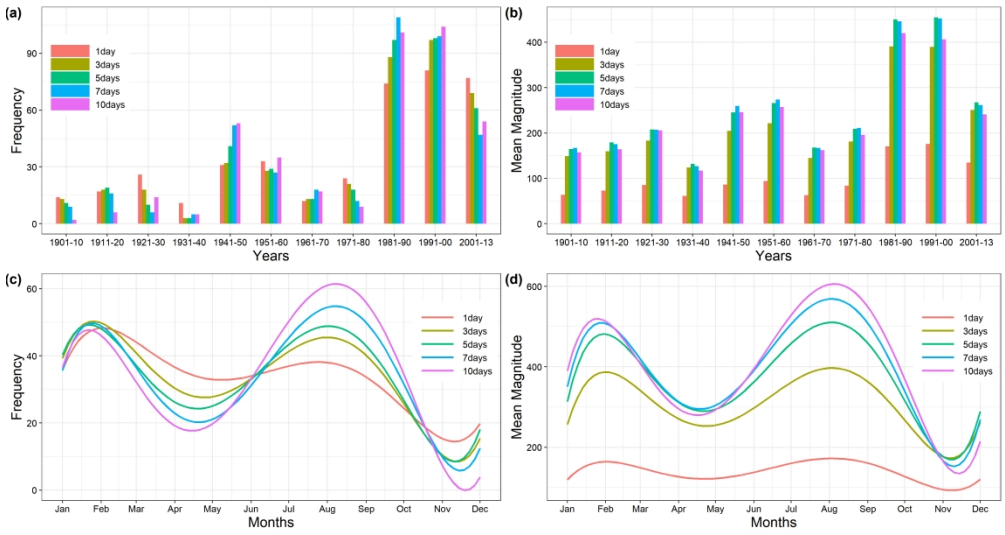

Figure 3: Distribution of precipitation extremes over IWH. Decadal distribution of (a) frequency, and (b) mean magnitude of top 1% extreme events for different durations. Monthly distribution of (c) frequency (d) and magnitude of top 1% extreme events for different durations.

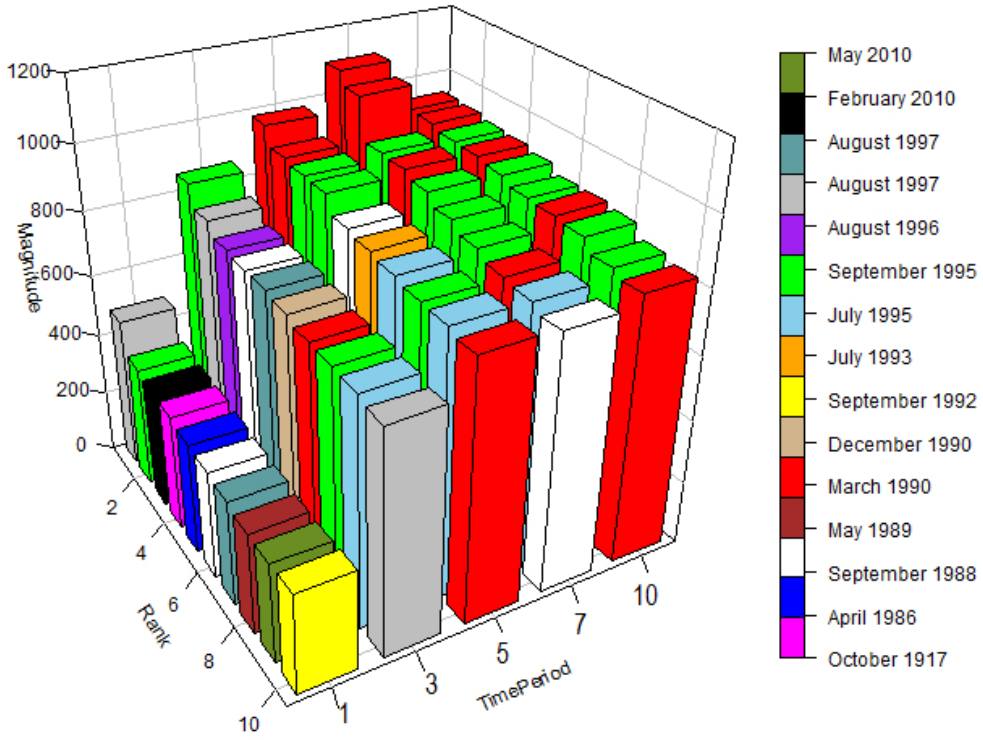

Figure 4: Magnitude (Rm) and rank for the top 10 events at different durations (1, 3, 5, 7, and 10 days) of accumulated precipitation. Arrowhead indicates the direction of increasing values.

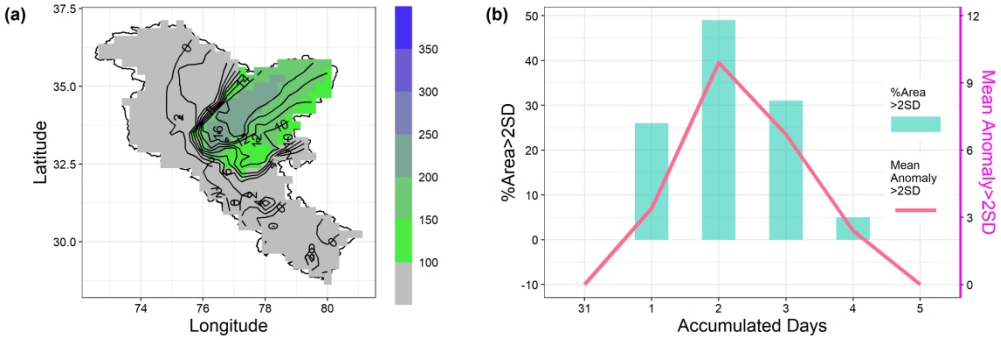

Figure 5: (a) Spatial distribution of accumulated precipitation (mm) and corresponding standard deviation anomalies (black contour) of a 1-day precipitation event occurring on 02-08-1997. (b) Spatial coverage and magnitude of the extreme event occurring between 31-07-1997 and 05-08-1997. Area means percentage of IWH with precipitation anomalies above 2 SD, magnitude is the mean of anomalies above 2 SD.

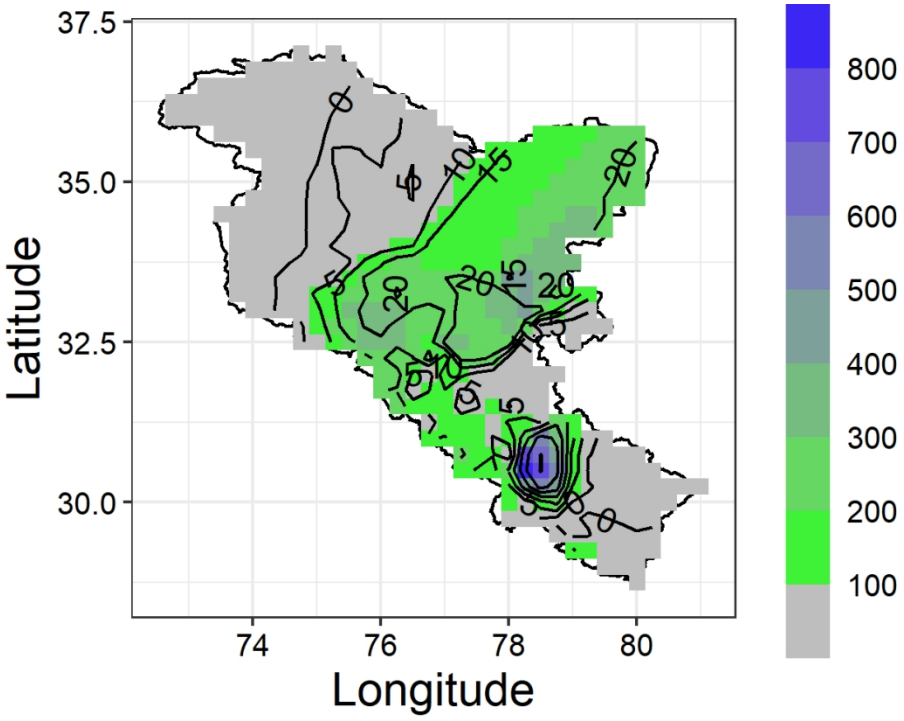

Fig. 6 Panel I- Spatial distribution of accumulated precipitation (mm) and corresponding standard deviation anomalies (black contour) of the 3-days precipitation event on 05-09-1995 i.e. from 03-09-1995 to 05-09-1995.

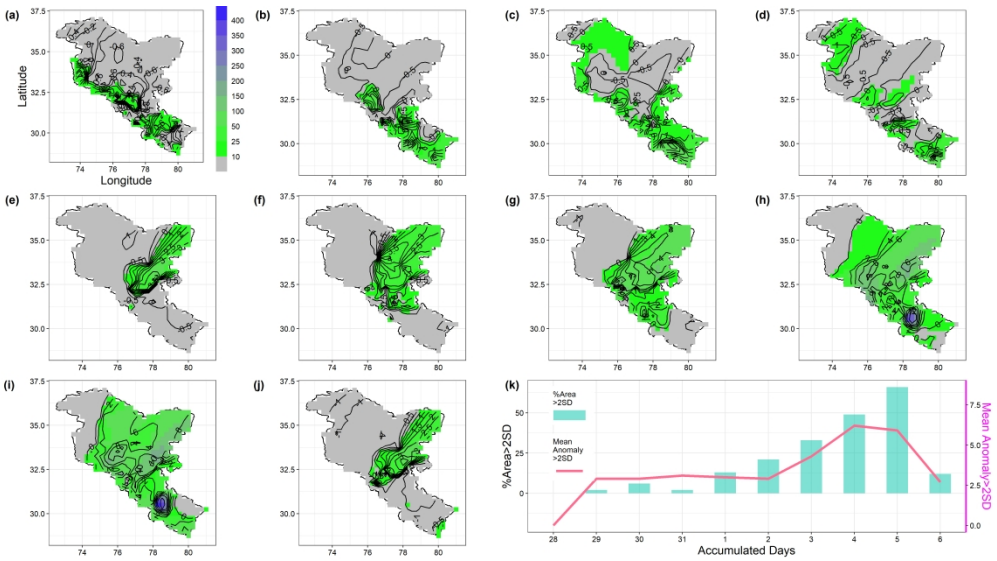

Figure 6:Panel II (a-j)- Spatial distribution of daily precipitation (mm) and corresponding standard deviation anomalies (black contour) of the 10-days period spanning between 28-08-1995 and 06-09-1995. (k) Spatial coverage and magnitude of the extreme event.

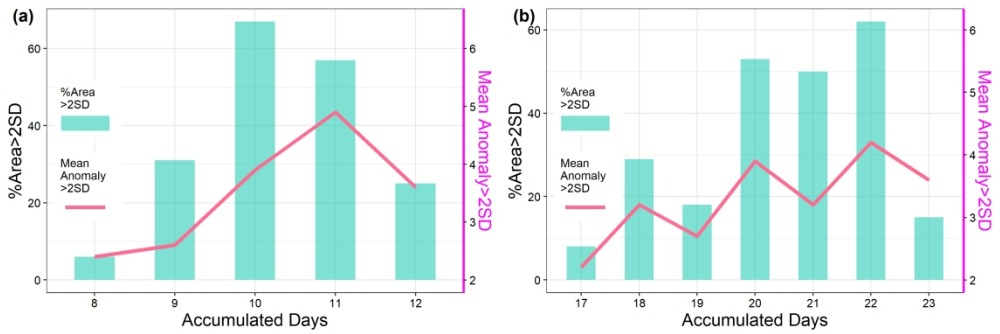

Figure 7: Daily evolution of the spatial coverage and magnitude of the extreme events on 12-07-1993 (a) and 22-03-1990 (b).

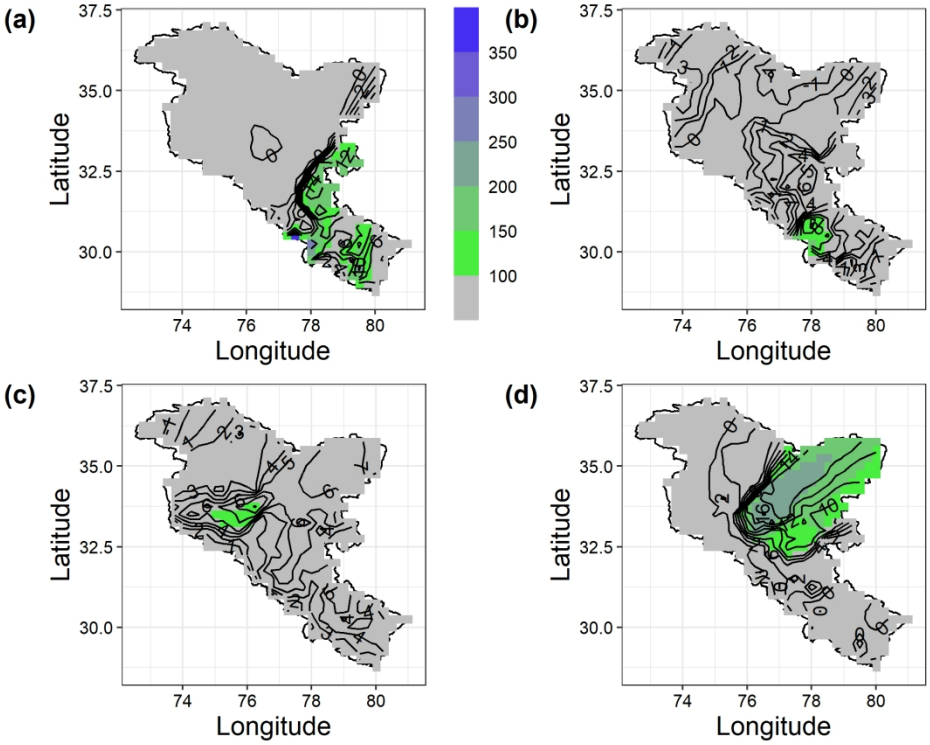

Figure 8: Spatial distribution of accumulated precipitation (mm) and corresponding standard deviation anomalies (black contour) during the Uttarakhand 2013 disaster and the top-ranked event at 1-day. (a-b) represent days during Uttarakhand floods, (c) and (d) are the rank 3 and rank 1 event, respectively.

Table 1: Top 10 extreme precipitation events in the Indian Western Himalayan for different durations (1, 3, 5, 7 and 10 days). For multi-day durations, dates correspond to the preceding days of accumulated precipitation. Thus, the 3-day top event on the 05-09-1995 corresponds to precipitation registered on 3, 4 and 5 of September.

Rank	1-Day	3-day	5-day	7-day	10-day
1	02-08-1997	05-09-1995	22-03-1990	23-03-1990	24-03-1990
2	05-09-1995	03-08-1997	23-03-1990	24-03-1990	25-03-1990
3	09-02-2010	24-08-1996	05-09-1995	05-09-1995	06-09-1995
4	27-10-1917	26-09-1988	06-09-1995	22-03-1990	26-03-1990
5	25-04-1986	29-08-1997	27-09-1988	06-09-1995	07-09-1995
6	25-09-1988	30-12-1990	12-07-1993	07-09-1995	08-09-1995
7	28-08-1997	22-03-1990	29-07-1995	08-09-1995	23-03-1990
8	02-05-1989	06-09-1995	07-09-1995	25-03-1990	05-09-1995
9	29-05-2010	28-07-1995	28-07-1995	29-07-1995	09-09-1995
10	10-09-1992	04-08-1997	24-03-1990	28-09-1988	27-03-1990

Table 2: Ranking index of contributing days to the disastrous Uttarakhand 2013 disaster as compared to the top-ranked event.

Plot	Date	% Area	Mean Anomaly	Ranking Index	Rank
(a)	17-06-2013	27	8.3	225	38
(b)	16-06-2013	40	3.9	156	96
(c)	09-02-2010	85	4.4	378	3
(d)	02-08-1997	49	9.9	483	1

Ranking and Characterization of Precipitation Extremes for the past 113 years for Indian western Himalayas

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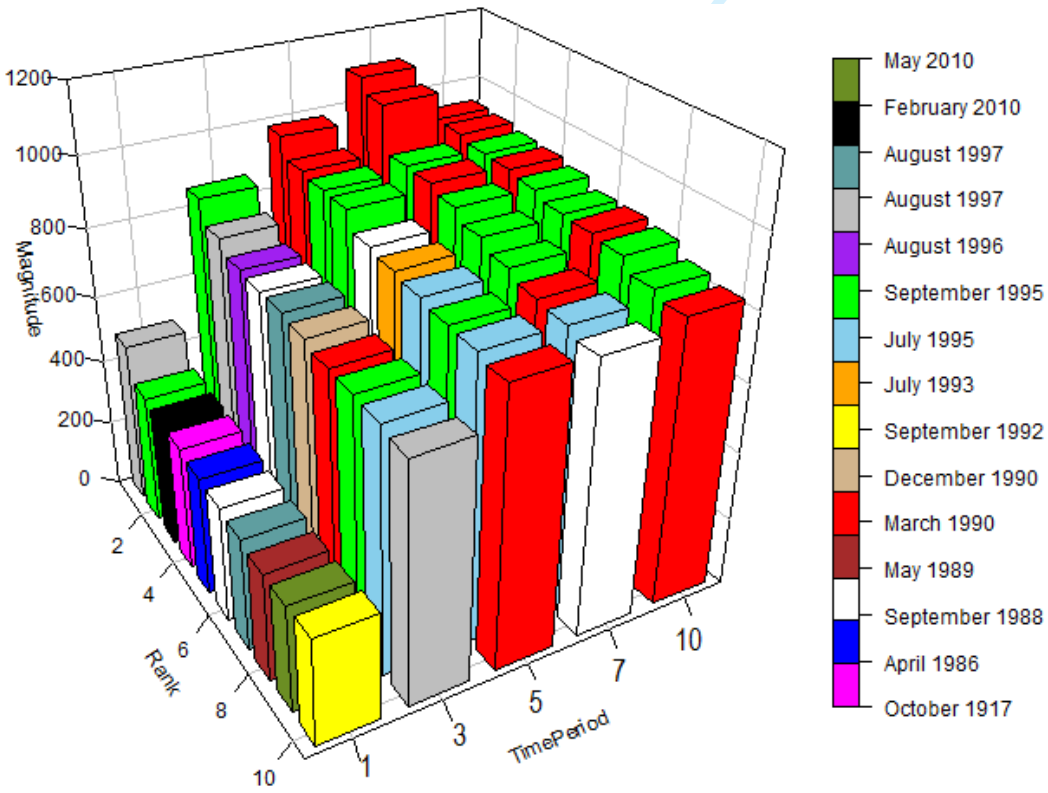
Highlights

- We use 113 years of precipitation data to rank precipitation extreme events in the Indian Western Himalayas, integrating precipitation spatial extent and its intensity across different time-scales
- Results show that the method accurately detects and ranks the most extreme precipitation events that occurred while delineating the spatial contours of these events.
- The proposed ranking method advances conventional single-day event ranking methods by accounting for multi-day duration providing meaningful information on the event duration associated with the highest impact on society.



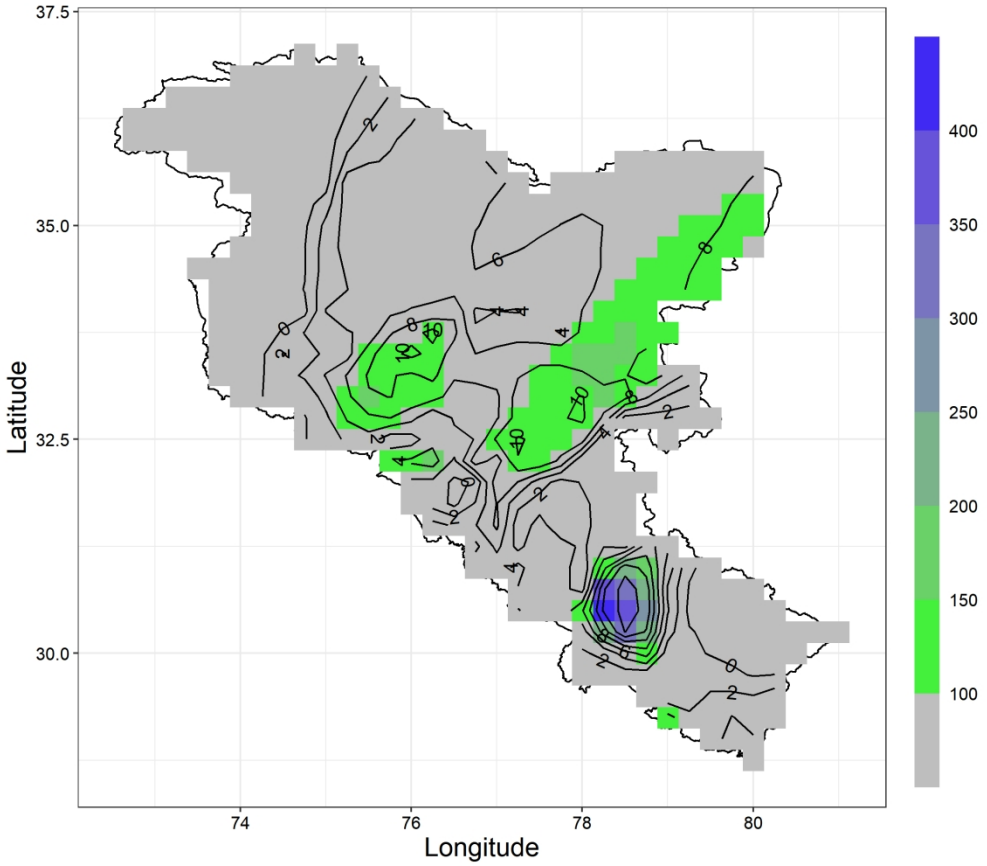


Figure S1: Spatial distribution and precipitation intensity of a particular event occurred on 05-09-1995.

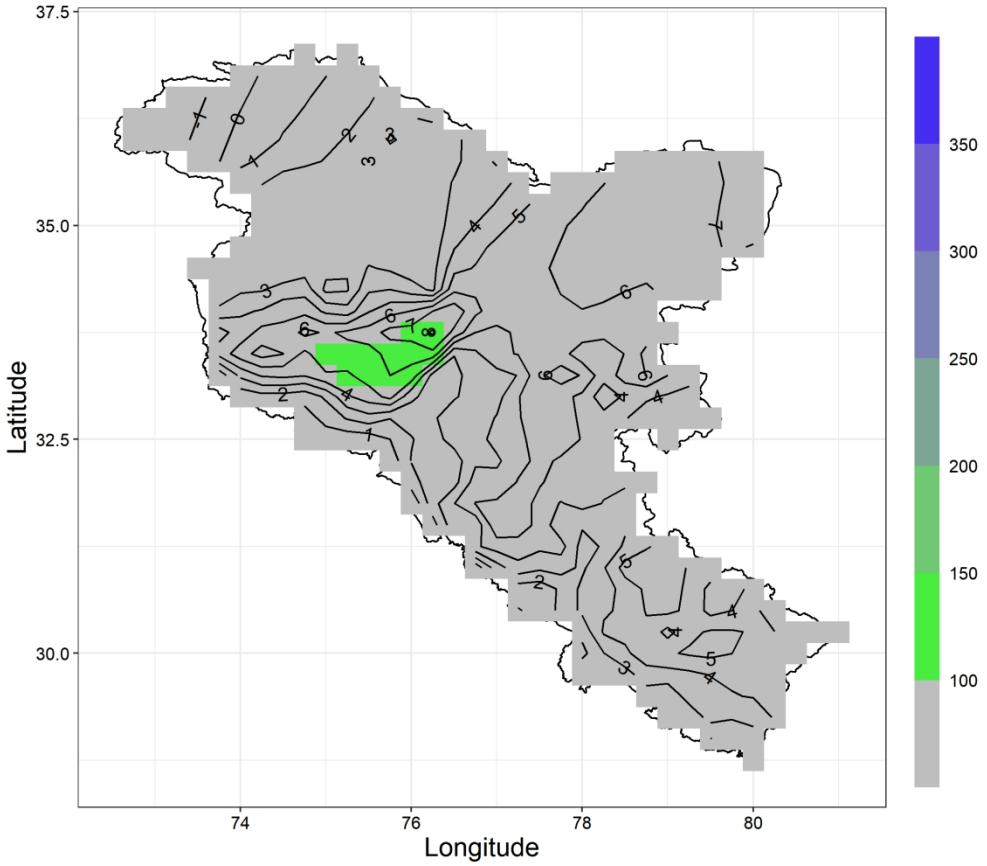


Figure S2: Spatial distribution and precipitation intensity of a particular precipitation event occurred on 09-02-2010.