The Pakistan flood of August 2022: causes and implications

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Key Points

- The southern provinces of Pakistan received more than 350% of average precipitation in July and August based on 2001-2021 mean.
- Extreme precipitation event in August is associated with atmospheric rivers.
- The frequency of similar precipitation events is projected to quadruple under the warming climate.

Abstract

The risk of floods has increased in South Asia due to high vulnerability and exposure. The August 2022 Pakistan flood shows a glimpse of the enormity and devastation that can further rise under the warming climate. The deluge caused by the Pakistan floods in 2022, which badly hit the country's southern provinces, is incomparable to any recent events in terms of the vast spatial and temporal scale. The 2022 Pakistan flood ranked third in human mortality, while this was the top event that displaced about 32 million people. Using observations and climate projections, we examine the causes and implications of the August 2022 flood in Pakistan. Multiday (~ 15 days) extreme precipitation on wet antecedent soil moisture conditions was the primary driver of the flood in August 2022. The extreme precipitation in August was caused by two atmospheric rivers that passed over southern Pakistan. Streamflow simulations from the multiple hydrological models show that extreme precipitation was the primary driver of floods as several stations in the flood-affected regions experienced anomalously higher flow than the stations located upstream. The frequency of similar multi-day extreme precipitation events is projected to rise four-fold under the high emission scenario. The 2022 Pakistan flood highlights the adapatation challenges that South Asia is facing along with the substantial need for climate mitigation to reduce the risk of such events in the future.

1. Introduction

The frequency of extreme weather events has considerably increased across the globe under the warming climate (Chinita et al., 2021; Lehmann et al., 2015; Papalexiou & Montanari, 2019; Westra et al., 2014; IPCC WG1, 2021; Seneviratne et al., 2021). However, the impact of extreme events is unarguably the highest in the developing countries of South Asia due to higher vulnerability and exposure (Mirza, 2011; Owusu et al., 2019). Every catastrophic extreme event pushes these nations further down the development conundrum (Haque, 2003; Mall et al., 2019; Shaw, 2022; Wijngaard & et al., 2018; Yadav & R. Lal, 2018;Haque, 2003; Mall et al., 2019). South Asian countries are widely impacted due to floods in the summer monsoon season (June-September), causing enormous destruction to life and livelihood than in any other parts of the world (Almazroui et al., 2020; Douglas, 2009). In South Asia, floods affected more than one billion people in the past 20 years (EM-DAT, https://public.emdat.be/data). Extreme floods are rising in South Asian countries (Mirza, M., 2011) and are projected to occur more frequently in the future under the warming climate (Alfieri et al., 2017; Hirabayashi et al., 2013). Thus, South Asia must adapt and mitigate the rising risk of floods.

The 'monster' flood of August 2022 in Pakistan, preceded by a devastating heat wave in May, has disproportionately impacted the country's southern provinces (Bhutto, 2022; Jones, 2022; L Otto et al., 2022). The flood affected one-third of the fifth largest populous country in the world, internally displacing about 32 million people and causing 1486 deaths, which include 530 children (Bhutto, 2022; Khokhar, 2022; NDMA, 2022; UNICEF, 2022). The economic losses are estimated to be over $30 billion (Bhutto, 2022; L Otto et al., 2022). In addition to the direct impacts, famine due to the widespread devastation of agricultural fields and possible disease outbreaks in temporary shelters are forthcoming (Baqir et al., 2012; Sarkar, 2022).

What caused the 2022 devastating flood in Pakistan remains an important question to be addressed. However, multiple reasons have been cited as a trigger for the August 2022 flood event, which includes heavy rainfall, glacial-melt contribution, and an intense low-pressure system developed over the land area due to the summer heatwave (Aziz, 2022; Jones, 2022; Mallapaty, 2022). Pakistan has received multiple spells of heavy monsoonal precipitation since the mid of June 2022, amplified mainly by the intense-low pressure system (Mallapaty, 2022). In addition, over seven glacial lake outbursts due to summer heatwaves increased the flow rate in the upper tributaries of the Indus river (UNDP, 2022; Jones, 2022). The 2022 flood reportedly crossed the peak flow rate in the devastating floods in 2010 over Pakistan (Bhutto, 2022). Moreover, the 2022 event is similar to the 2010 event in the existence of a La-Nina and Rossby formations in the high-altitude jet streams (Aziz, 2022; Di Capua et al., 2021; Hong et al., 2011). The 2010 flood event was intensified by anthropogenic forcing (Hirabayashi et al., 2021), while another study (Christidis et al., 2013) did not report any reliable climate attribution statement for the causative precipitation event. Therefore, understanding the role of anthropogenic warming on the occurrence of devastating events is indispensable for devising adaptation policies for the future.

Pakistan faces multiple threats due to climate change, including glacier melt, extreme precipitation, floods, droughts, and sea-level rise (Hunt et al., 2018; Khan et al., 2019; Nasm et al., 2018; Schrier et al., 2018). Moreover, based on the climate deluges experienced from 2000-2019, Pakistan is among the top ten countries in the global climate risk index, highlighting the climate vulnerability from extreme events (Eckstein et al., 2021). Proper identification of the prominent flood drivers associated with the August 2022 flooding event is necessary for building resilience. Here, we investigate the predominant cause of the August 2022 flood in these regions and estimate the probability of occurrence of these drivers in the projected future climate. We address the following questions: (1) Can extreme precipitation events entirely explain the August 2022 flood in Pakistan? (2) what caused the anomalous extreme precipitation, and how likely are similar events in the projected warming climate? and (3) How anomalous was the 2022 flood event that caused considerable damage in Pakistan?

1. **Data and methods**

Datasets

We obtained NASA's Level 3 Integrated Multi-satellite Retrievals for Global Precipitation Mission (GPM) 3IMERGHHL v06- Late Run (https://disc.gsfc.nasa.gov), commonly known as the multi-satellite precipitation estimate with climatological gauge calibration. The precipitation data is available at 0.1° spatial resolution from June 2000 to August 2022 (Hou et al., 2014; Liu & Zipser, 2015). The precipitation product is derived by combining observations from multiple passive microwave satellites in the GPM constellation using the IMERG algorithm. GPM accurately captures the Spatio-temporal variability in precipitation in tropical regions and is widely used for the analysis of extreme precipitation (Arshad et al., 2021; Pradhan, et al., 2022).

We obtained the gridded Land Parameter Retrieval Model (LPRM) soil moisture data products from EarthDATA for estimating the antecedent soil moisture conditions before extreme precipitation. Daily soil moisture data is available at 10 km spatial resolution. The gridded soil moisture product is developed by converting the observed brightness temperature measured by the microwave sensor (ASMR2) into soil moisture using the multi-parameter retrieval algorithm (Owe et al., 2008). We used two products, 'ascending' for daytime and 'descending' for nighttime that provide the volumetric soil moisture percentage in the top 20 cm soil layer. These datasets have been extensively validated against the in situ data, model output, and other satellite products (Holgate et al., 2016; Kim et al., 2015; Parinussa et al., 2011).

We obtained atmospheric variables at the surface level from the 5th generation European Centre for Medium-Range Weather Forecasts (ECMWF) [ERA5; Hersbach & Dee (2016)] for estimating the atmospheric characteristics associated with extreme precipitation events. We used vertically integrated eastward and northward water vapour flux, zonal and meridional components of wind vector at 850hPa, mean sea level pressure (MSLP), and total column water vapour (TCWV) for the analysis. ERA5 atmospheric data is widely used as it provides reliable information for hydrometeorological applications in South Asia (Mahto et al., 2019; Vijaykumar et al., 2021).

We used simulations from nine global climate models (GCMs) [Table S1] that participated in the Climate Model Intercomparison Phase 6 (CMIP6) for the historical (1951-2014) and future periods (2015-2100). We used simulations from CMIP6-GCMs for three shared socioeconomic development pathways (SSP1-2.6, SSP2-4.5 and SSP5-8.5). SSPs are defined by the Scenario Model Intercomparison Project (O'neill et al., 2016) that combines the alternative growth of society in the absence of climate change with possible emission trajectories. For instance, the SSP1 describes optimistic development of society with adequate investment in health and education, while the SSP5 describes an energy-intensive pessimistic society (Riahi et al., 2017). The forcing pathways of SSP1-2.6, SSP2-4.5 and SP5-8.5 stabilize at 2.6, 4.5 and 8.5 W/m^2, respectively, by the end of the 21^{st} century. We selected the three SSP scenarios so that the difference among the scenarios can highlight the benefit of climate change mitigation. The selected nine CMIP6-GCMs reproduce precipitation variability over south Asia (Aadhar & Mishra, 2020; Rajendran et al., 2021).

Satellite-based Flood Extent Mapping

We used Synthetic Aperture Radar (SAR) and Moderate Resolution Imaging Spectroradiometer (MODIS) for flood mapping (Brakenridge & Anderson, 2006; Notti et al., 2018; Twele et al., 2016). Vertical-Horizontal (VH) polarization and backscatter information from SAR was used to derive the preliminary flood extent (H. Cao et al., 2019; Moharrami et al., 2021; Zhang et al., 2020). We estimated VH and backscatter before and during the flood inundation. The grid cells with the ratio of backscatter before and after flood exceeding 1.2 are classified as the preliminary flood extent (Landuyt et al., 2019; Twele et al., 2016). Further, slope and connectivity information is used for updating the preliminary extent. We obtained the area of permanent water bodies from MODIS Terra daily reflectance data, which is used for further refining the results. Finally, we combined SAR and MODIS data and performed visual validation of major cities using optical data from sentinel-2 (see Supplementary Table S2).

Models and analysis

We used four calibrated physical hydrological models: Variable Infiltration Capacity (VIC), NOAH-MP, Community Land Model (CLM), and H08, coupled with a routing model (Lohmann et al., 1996) for streamflow simulations (Kushwaha et al., 2021). These land surface hydrological models were calibrated against in-situ and satellite-based observations in the Indian sub-continental river basins ((Kushwaha et al., 2021). The input datasets, physical processes, and calibration parameters of these models are listed in Table S3-S5. Due to the lack of daily streamflow observations at the downstream reaches of the Indus basin for calibrating the hydrological models, we use the ensemble simulations from the four models for the analysis. The ensemble streamflow simulations can reduce the uncertainty emerging from inadequate calibration of the hydrological models (Hardy et al., 2016; Mishra et al., 2018; Kushwaha et al., 2021). The four hydrological models capture the seasonal variability of monthly streamflow at Panjnad, an upstream location in the Indus basin (Figure S3).

Initially, we identify the region that received extreme precipitation events in July and August 2022 using the spatial distribution of daily precipitation derived from GPM. After identifying the main precipitation event, we used daily soil moisture observations to estimate the antecedent soil moisture conditions before the precipitation event. Further, we used the ERA5 atmospheric variables to investigate the atmospheric characteristics associated with extreme precipitation events. We also investigated the presence of atmospheric rivers (ARs) during extreme precipitation events. Finally, using the four land surface models, we obtained streamflow simulations at multiple locations along the flooded stretch.

Identification of atmospheric rivers (ARs)

We used a threshold-based AR identification methodology developed by Guan and Waliser (2015) to examine if AR was present during the extreme precipitation that caused flooding in August 2022. Initially, we estimated the integrated vertical moisture transport (IVT) magnitude ($kg.m^{-1}.s^{-1}$) using vertically integrated eastward (q_u) and northward (q_v) water vapour flux from ERA5 (equation 1).

IVT = $\sqrt{{q_u}^2 + {q_v}^2}$ (1)

A threshold of 85^{th} percentile of daily IVT at each grid cell is used instead of a fixed-value threshold to account for the large spatial and temporal variability in IVT (between 150-500 $kg.m^{-1}.s^{-1}$) over the south Asian region (Liang & Yong, 2021; Lyngwa & Nayak, 2021). In addition to the 85^{th} percentile criteria, IVT values at any grid point should be greater than 150 $kg.m^{-1}s^{-1}$ to ensure strong moisture transport (Guan & Waliser, 2015), specific to the South Asian monsoonal climate (Liang & Yong, 2021).

First, we identified the grids with an IVT greater than 85^{th} percentile of the climatological IVT and make clusters out of contiguous grids in the region (40-85E, 0-35N), termed as preliminary atmospheric rivers. The length (L) of AR is calculated by joining the grids of maximum IVT within a qualified cluster (Liang and Yong 2021). The width (W) of AR is defined as the ratio of area and length, which was further used to calculate the length-to-width ratio (LW ratio) for isolated contiguous clusters. The circularity index (CI=1, representing a perfect circle) was also estimated to distinguish ARs from tropical cyclones, as both are characterized by high IVT. The geometric thresholds were ($L > 2000$km, LW ratio>2, and $CI<0.5$) and then applied to identify the final atmospheric rivers. Persistent ARs for two days or more were considered a single AR event, where the total number of continuous days in the event provides the duration of an AR.

3. Results and discussion

The 2022 flood: was it unprecedented?

Satellite-based (see methods for details) flood inundated areas show that the 2022 flood in Pakistan considerably affected the southern provinces, including Balochistan, Sindh, and Khyber Pakhtunkhwa (L Otto et al., 2022; NDMA, 2022) [Fig. 1]. The monsoon rainfall in the southern provinces exceeded more than five times the climatological average in these regions, causing massive destruction to life and property (OCHA, 2022) [Fig. 1]. The rainfall in August 2022 exceeded 500 percent of the climatological mean in Sindh and Balochistan (Chughtai, 2022; PMD, 2022). The 2022 flood event caused significant mortality (~ 1500 human lives) and ranks third after the major floods in 1992 (2750 human lives) and 2010 (1750 human lives) (Table 1). The flooding caused the formation of the massive lake in the Sindh and Balochistan provinces due to inundation (L Otto et al., 2022; Mallapaty, 2022) [Fig. 1]. The densely populated area on the right bank of Indus was submerged, and the event affected 33 million people across several considerably populated cities (Fig. 1b). The 2022 flood displaced more than 32 million people, which is the highest among all the events that caused the death of over 100 people (Table 1). The flood caused an estimated economic loss of $30bn and affected four million hectares of agricultural land that predominantly included cotton fields (Chughtai, 2022; L Otto et al., 2022; NDMA, 2022) [Fig. 1b]. The frequency and damage caused by major floods are rising in Pakistan, as 14 of the top 21 events occurred after 2000 (Table 1).

Extreme precipitation is a major driver of the 2022 flood

Next, we examined the intensity and duration of the precipitation that caused a massive flood in Pakistan in August 2022. Based on the satellite data (see method for more details), we analyzed spatial patterns associated with precipitation at multiple durations during July and August 2022 to demarcate the region that received heavy precipitation (Fig. 2a). We identified the region based on the 15 days accumulated precipitation that overlaps with the flood affected areas (Fig. 1). Several regions experienced 15-day accumulated precipitation greater than 400 mm, which is anomalous compared to the climatological distribution of rainfall in the region. The highest two-day extreme precipitation occurred on 17-18 August (Fig. 2a-b), while the highest daily precipitation (92mm) occurred on 18th August. The extreme daily precipitation exceeded the 99.9th percentile of rainy days based on the 2001-2021 long-term mean. We find many days in August 2022 that experienced more rainfall than the 99th percentile threshold.

The monthly precipitation in August 2022 in the flood-affected region exceeded two standard deviations from the mean rainfall of the 2001-2021 period. However, the region experienced July 2022 precipitation lower than the long-term mean (Fig. S2). Similarly, the cumulative daily precipitation (mass-curve) from July to August 2022 exceeds two standard deviations of the climatological mean (2022-2021) [Fig. 2c]. The mass curve exhibits a considerable rise in rainfall from 17-18th August 2022. The significant departure of the mass curve from the climatology indicates the anomalous precipitation received from 17-24th August. Usually, the flood-affected region receives a total rainfall depth of 200$\pm$120mm in July and August. However, in 2022, the total rainfall depth was around 900mm, almost 350% higher than the long-term (2001-2021) average. The spatial anomaly of monthly precipitation depicts considerable higher precipitation in August 2022 compared to July 2022 (Fig. S1). The flood-affected region witnessed continuous precipitation from July through August 2022. However, the precipitation from 17-24th August was considerably intense, highlighting the anomalous nature of the event. The continuous rainfall for multiple days can trigger favourable conditions for floods due to wet antecedent conditions (Berthet et al., 2009; Nanditha & Mishra, 2022; Wasko et al., 2020). Therefore, we hypothesize that the massive flood in August 2022 in Pakistan is a culmination of a multiday extreme precipitation event that occurred on wet antecedent soil moisture conditions.

The role of antecedent soil moisture

Antecedent moisture conditions played an important role in the August 2022 flood in Pakistan. Floods occur due to multiple factors, of which extreme precipitation and antecedent soil moisture play a considerable role (Berghuijs et al., 2016; Nanditha & Mishra, 2022; Sharma et al., 2018). Extreme precipitation on wet antecedent soil moisture conditions has a higher probability of flooding (Ivancic & Shaw, 2015; Wasko & Nathan, 2019). Positive soil moisture anomalies persisted across the flood-affected region at different durations ending on 15th August (Fig. 3a). Daily soil moisture reached to the highest level on 15 August and exceeded the 99th percentile of the climatological mean soil moisture (2013-2021) [Fig. 3b]. The presence of wet soil moisture conditions before the extreme precipitation event in August contributed to the flooding. The wet soil moisture conditions created conducive conditions for extreme precipitation, translating to a major flood event. The occurrence of highly anomalous precipitation on wet antecedent soil moisture conditions is a prominent factor that led to flooding.

Atmospheric characteristics associated with extreme precipitation events

Next, we investigated the atmospheric drivers associated with the extreme precipitation events in August 2022 to identify the unique atmospheric characteristics that caused the event. Two extreme precipitation spells occurred between 16th and 25th August (Fig. 2b), and the anomalous nature of extreme rainfall points towards the possible occurrence of atmospheric rivers (ARs). The two distinct ARs passed over Pakistan during the extreme precipitation period (Fig. 4). The first AR passed from 16 to 18th August and lasted for three days, whereas the second AR passed on 23rd August. Among the four AR days, three days (17, 18 and 23 August) received daily precipitation greater than the 99.5 thresholds (Fig. 2b). Integrated Water Vapour Transport (IVT) intensity greater than 600 kg/m/s persisted during both the ARs, fueling enormous moisture considering the arid conditions in southern Pakistan. The AR during 16-18th August was of category five (maximum IVT more than 1000 kg/m/s and duration higher than 48hours). In contrast, the AR on the 23rd August was the category four event (maximum IVT more than 1000 kg/m/s and duration more than 24-48 hours) based on the strength and impact (Ralph et al., 2019). A relatively low mean sea level pressure developed over the flood-affected region during the ARs (Fig. 4b, d). ARs caused an anomalously high (more than 80mm) accumulation of total column water vapor (TCWV), indicating the presence of deep convective clouds over the region (Fig. 4b, d).

Extreme precipitation due to ARs has commonly been reported in many parts of the globe since they can carry vast amounts of moisture in the lower troposphere (Algarra et al., 2020). For instance, California in the US experienced more than 95% of extreme precipitation due to ARs during 1951-2015 (Q. Cao et al., 2019, 2020). ARs in the south Asian region usually pass over the peninsular and eastern India, exclusively during the June-September period (Liang & Yong, 2021; Pan & Lu, 2019). However, a few ARs move towards northern or northwest India. One such incident caused the Kedarnath floods in 2013 in India when AR developed in northwest India (Lakshmi et al., 2019). The ARs in August 2022 falls among the rare events that were fueled by strong westerly winds and a low-pressure system over the Pakistan region that pulls moisture from the adjoining Arabian Sea (Fig. 4). Overall, extreme precipitation events that led to the Pakistan flood were associated with atmospheric instability with high IVT, strong westerly winds, high water vapor, and a low-pressure system.

Streamflow simulations of the 2022 flood event

We conducted simulations using the four hydrological models (see method for more details) to obtain streamflow at different locations in the flood-affected region in the Indus river basin. We simulated streamflow at Kotri (downstream), Panjanad (upstream), and four other locations in the flood-affected region in the Indus River basin (Fig. 1 and 5). The difference in streamflow simulations at Panjanad (upstream) and Kotri (downstream) helps us understand the impact of extreme precipitation. The annual maximum streamflow in 2022 exceeded the 99.9^{th} percentile threshold (of 2022-2021) of annual maximum flow at all the stations, except at Panjanad, located in the upstream region and primarily affected by the glacier melt flow. Similarly, streamflow departure for the 2022 event from the average annual maximum flow is the lowest for upstream flow station (departure less than 10%, Table S6) compared to the locations in the flood-affected region. On the other hand, the stations in the flood-affected region witnessed a 300% rise in flow from the long-term average (Fig. 5h). Extreme precipitation (16-24 August) along with wet antecedent soil moisture conditions translated to higher streamflow values at the four locations in the flood-affected region and resulted in considerably higher streamflow at Kotri (Fig. 5h).

We further examined daily streamflow for July and August at all six stations (Fig. S2). A distinct peak flow event was found at the end of August at the four locations that are in the flood-affected region. However, there is no distinguishable peak in August at Panjanad, which is located upstream of the major precipitation region. The major contribution to Kotri in August comes from the intermediate stations in the extreme precipitation region. Therefore, extreme precipitation played a crucial role in the August flooding of the southern provinces.

Future projections of extreme precipitation events

Floods result from complex interactions of land system drivers and atmospheric factors, which makes it complicated to develop reliable projections (Bertola et al., 2019; Blöschl et al., 2015; Sharma et al., 2018; Tarasova et al., 2019). Therefore, it is recommended to accurately identify the flood drivers and estimate the projected changes in these drivers in a warming climate, to ascertain the potential future changes in floods (Villarini & Wasko, 2021). Extreme precipitation under wet antecedent conditions is the prominent driver of the August 2022 flood in Pakistan.

We computed the frequency of extreme precipitation for the flood-affected region [24-30N, 66-71E] using nine CMIP6 global climate models (GCMs) for the three emission scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5). We estimated the frequency of extreme precipitation exceeds the 99^{th} percentile of rainy days (>1 mm) for the 2001-2014 reference period for 1950-2100. The frequency of extreme precipitation is projected to rise in all the warming scenarios. However, the highest increase in frequency is projected under SSP5-8.5 compared to SSP1-2.6 and SSP2-4.5 scenarios highlighting the importance of climate mitigation (IPCC, 2022). Moreover, multiday precipitation at seven-day and ten-day durations has a higher rate of the projected increase in the frequency of extreme precipitation than at the other durations. The frequency of seven-day and ten-day precipitation is projected to quadruple by the end of the 21^{st} century in the SSP5-8.5 scenario. In contrast, the frequency of one-day and three-day precipitation is projected to double. Multiday precipitation encompasses extreme precipitation and antecedent soil moisture conditions and is more likely to translate to floods (Bertola et al., 2019; Nanditha & Mishra, 2022). Therefore, the projected increase in the frequency of seven-day and five-day extreme precipitation has substantial implications for floods in this region under the warming climate (Bertola et al., 2019; Nanditha & Mishra, 2022; Tramblay et al., 2021).

1. **Summary and conclusions**

We examined the causes of flooding in the downstream reaches of the Indus basin in Pakistan, which resulted in massive destruction of life and property. The flood-affected region witnessed an extreme precipitation event that occurred from 16 -24^{th} August in Pakistan's Sindh and Balochistan provinces. Extreme precipitation was the main driver of the 2022 flood in Pakistan. Extreme precipitation on extremely wet soil moisture results from prolonged precipitation in July and early August. Also, a distinguishable atmospheric river is associated with the precipitation event from 16-18^{th} August. The capacity of atmospheric rivers to carry a significant amount of moisture leading to heavy precipitation is well established (Q. Cao et al., 2019). Ensemble streamflow simulations from the four hydrological models at stations above and below the major flooded stretch emphasize the prominence of extreme precipitation in generating the peak discharge in August at Kotri, the downstream station. Further, we find the frequency of extreme precipitation events is projected to increase manifold by the end of the 21st century in a warming world.

Pakistan is highly vulnerable to glacial lake outburst floods (GLOF), with over 3000 glacial lakes in the country's northern mountain ranges (UNDP, 2022). Among the 3000 glacial lakes, 30 are susceptible to GLOFs. In addition, the deadly heatwave in March-May seriously impacted 30% of the land area and resulted in a GLOF in the country's northern provinces (Zachariah et al., 2022). The extreme rise in temperature led to the rapid melting of glaciers and significantly contributed to streamflow in the upper tributaries of the Indus river basin (Mallapaty, 2022). Quantifying glacial melt to streamflow in the Indus basin is necessary to ascertain the contribution of glacial melt to the August flooding in the southern provinces. However, our results suggest the extreme precipitation event in the southern regions with a 100-year return period was an immediate trigger to the flood event (L Otto et al., 2022). The glacial melt contribution due to the March-May heatwave could have exacerbated the flooding along with extreme precipitation but was not the primary driver.

Global temperature rise will increase the frequency of extreme precipitation events (O'Gorman, 2015; Pfahl et al., 2017) as warm air can hold more atmospheric water vapour (E. K. Trenberth, 2011; K. E. Trenberth et al., 2003). Our results indicate that extreme precipitation conditions are likely to occur more frequently in the region, as reported in previous studies (Seneviratne et al., 2021). With record-breaking extreme precipitation in the future, the flood risk will also increase in the region. Therefore, strong adaptation measures are crucial in building a climate-resilient future in flood-prone communities in the wake of a future with more frequent disasters (Caretta et al., 2022, O'Neill et al., 2022; Shaw et al., 2022). Our findings directly affect long-term hazard mitigation and climate adaptation across this region.

There is a considerable disparity in the adaptation gap in lower-income countries compared to developed counterparts (IPCC,2022; O'Neill, 2022). The extent of flood damage in 2022 highlights the need for structural and non-structural flood control measures, both of which requires a significant investment (Caretta, 2022; Codo & Rico-Ramirez, 2018; Silvestro et al., 2019; Sukla, 2020). Implementation of long-term adaptation measures requires adequate funding and support from developed countries that primarily contribute to global emissions. Pakistan contributes less than one per cent of global greenhouse gas emissions (Aziz, 2022; Bhutto, 2022), so a concerted effort by the developed countries is crucial in building resilience in low-emission countries with high climate exposure.

Acknowledgement: We acknowledge data availability from ERA5 reanalysis: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, GPM: https://gpm.nasa.gov/data, Sentinal: https://sentinels.copernicus.eu/web/sentinel/sentinel-data-access, soil moisture from EarthData: https://www.earthdata.nasa.gov/, and CMIP6 model output: https://esgf-node.llnl.gov/projects/cmip6/ .

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Table

Table 1. Table shows the 2022 flood event in the context of the top 20 flood events in Pakistan that led to the death of more than 100 people. The year of the flood, area affected which includes the area of neighbouring countries

affected in that year, people dead and displaced, major cause and severity, and neighbouring countries affected by floods are listed in the table. The majority of the events were caused due to monsoonal rains, and among the 21 events, 14 occurred post 2000s. Data obtained from the international disaster database, EM-DAT (https://public.emdat.be/data).

*Approximate area is marked. The survey of flood affected area is currently undergoing (NDMA, 2022).

Sl. No.	**Year**	**Area (km^2)**	**Dead**	**Displaced**	**Major cause**	**Severity**	**Other affected c**
1	1992	873375.01	2750	3000000	Monsoonal rain	2	India
2	2010	129691.63	1750	10000000	Monsoonal Rain	2	0
3	**2022**	**265365.00***	**1496**	**32000000**	**Monsoonal Rain**		**0**
4	1995	672265.35	600	600000	Monsoonal rain	1	0
5	2011	32667.16	434	660000	Monsoonal Rain	1.5	0
6	2012	23036.11	400	742000	Monsoonal Rain	1.5	0
7	1994	343251.55	333	30000	Monsoonal rain	1	0
8	2014	253686.93	300	30000	Monsoonal Rain	2	India
9	1998	165619.86	300	240000	Heavy rain	1	Iran
10	2005	123212.59	300	40000	Heavy rain	1	0
11	2003	868200.94	285	900000	Monsoonal rain	1	India
12	2007	115766.52	280	400000	Tropical cyclone	1	0
13	2006	182706.86	248	0	Monsoonal rain	1	India
14	2001	111090.8	230	40000	Brief torrential rain	1	0
15	2007	2215.04	230	0	Monsoonal rain	1	0
16	1999	59617.85	168	200000	Tropical cyclone	1	
17	2015	137039.96	166	803000	Monsoonal Rain	1.5	0
18	1997	276909.38	165	836300	Monsoonal rain	2	0
19	1988	220520.86	158	163000	Monsoonal rain	1	Afghanistan
20	2013	549425.38	135	81000	Heavy Rain	1.5	India
21	2007	29411.27	130	2000	Heavy rain	1	India

Figures

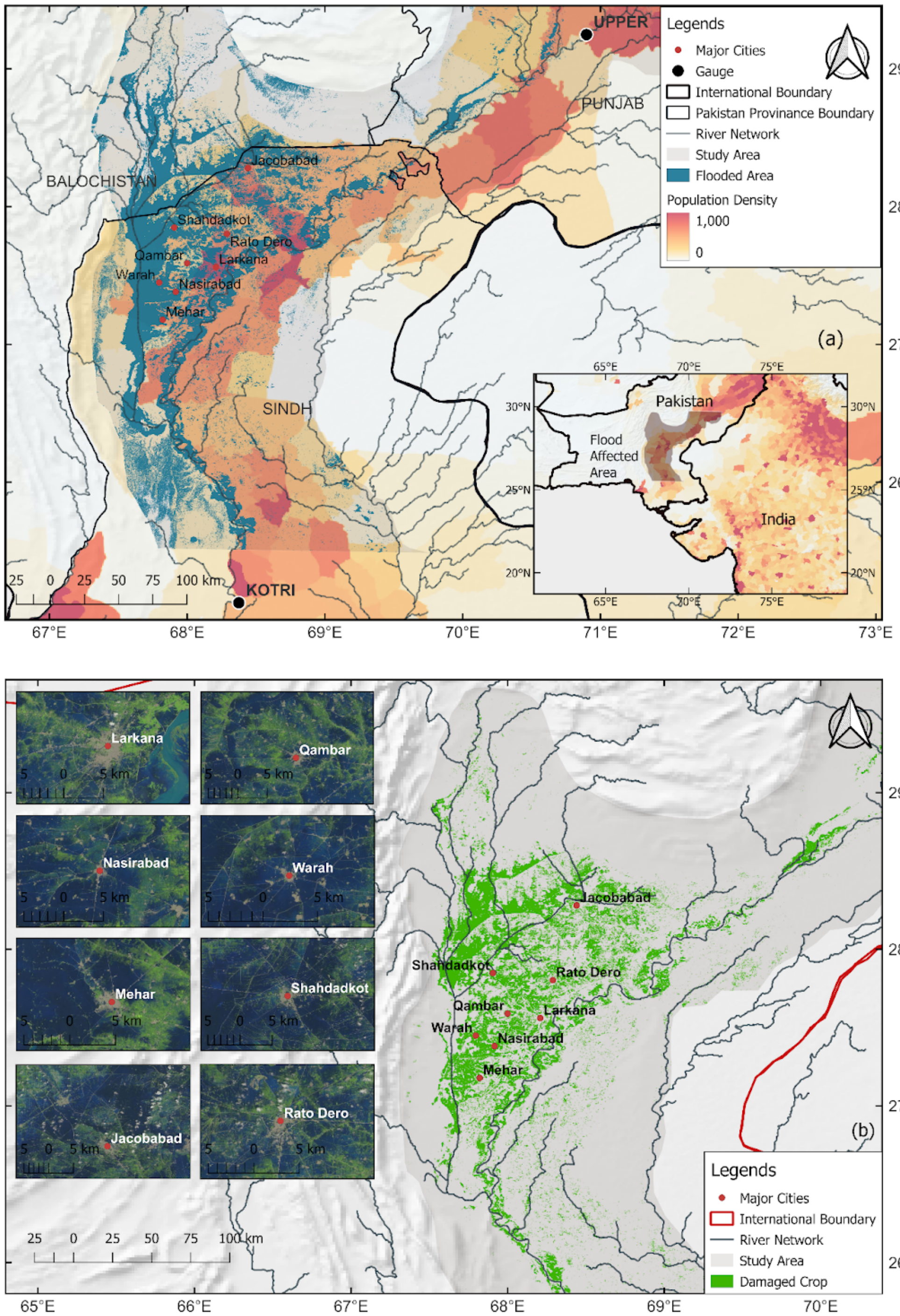
Legends
Major Cities
Gauge
International Boundary
Pakistan Provinance Boundary
River Network
Study Area
Flooded Area
Population Density
1,000
0
UPPER
PUNJAB
BALOCHISTAN
SINDH
KOTRI
Jacobabad
Shahdadkot
Rato Dero
Qambar
Larkana
Warah
Nasirabad
Mehar
Pakistan
Flood Affected Area
India
(a)
(b)
Legends
Major Cities
International Boundary
River Network
Study Area
Damaged Crop

Figure 1. (a) Map of flood extent and the population exposed to flooding. 1(a) shows the flood-affected region in the southern provinces of Pakistan. The densely populated right bank of the Indus river is majorly affected by flooding. Major affected cities are marked on the figure. The location of the upstream and downstream stations (Panjanad and Kotri, respectively) at which streamflow values are simulated are also indicated in the figure. The flood extend is prepared using Sentinel-2 and MODIS satellite data. Detailed information is provided in the supplementary section. Figure 1b shows the crop areas affected during the 2022 flood vent. The crop data is obtained from Sentinel-2 based ESRI LULC classification at 10m spatial resolution. The inset figures, generated using sentinel-2, depict the true color images of flood extent in the major cities.

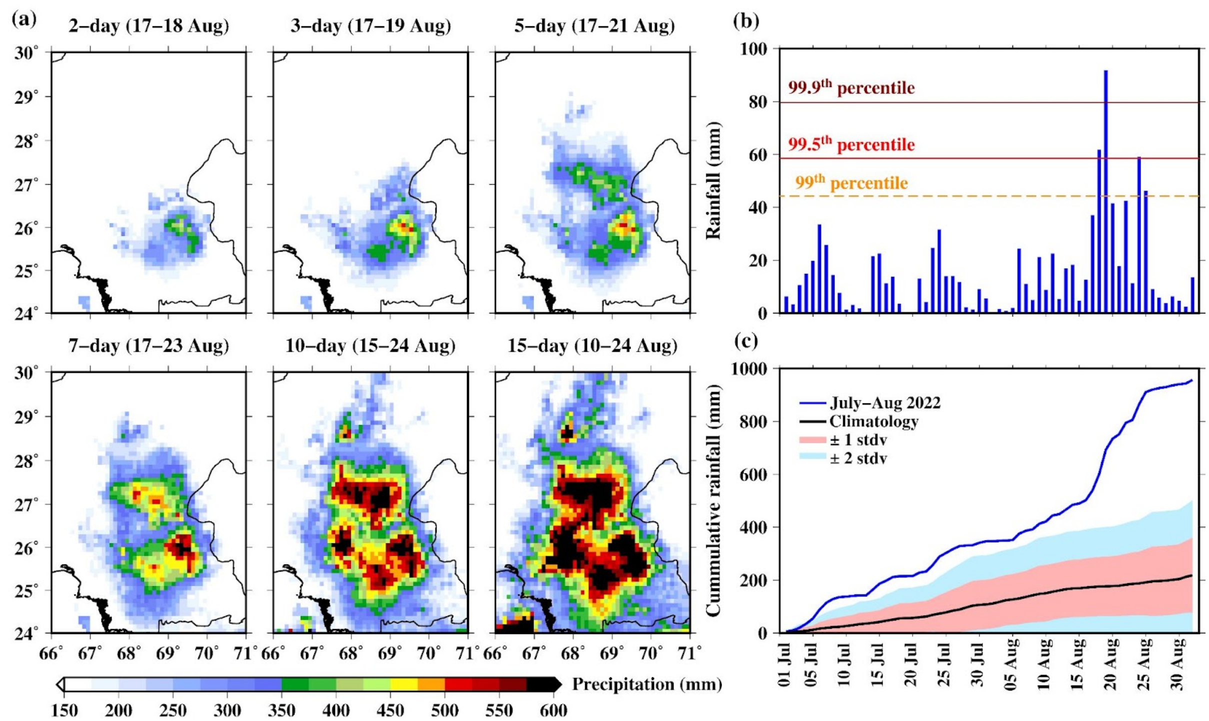

Figure 2. Precipitation extent during the 2022 flood in Pakistan. (a) Multiday precipitation during August 2022. (b) Observed daily precipitation (mm) over the study region (continuous grids with 15-day precipitation >400 mm). Different thresholds of rainy day (>0.2mm) daily precipitation from 2001-2021 is marked in the figure. (c) Cumulative rainfall from 1 June to 31 August 2022 (blue) and its climatology (black) for the study area. The shaded region shows the first (red) and second (blue) standard deviations from the climatological mean. The satellite based precipitation from GPM-IMERG (2001-2022) is used to analyse the extreme precipitation during the 2022 flood event.

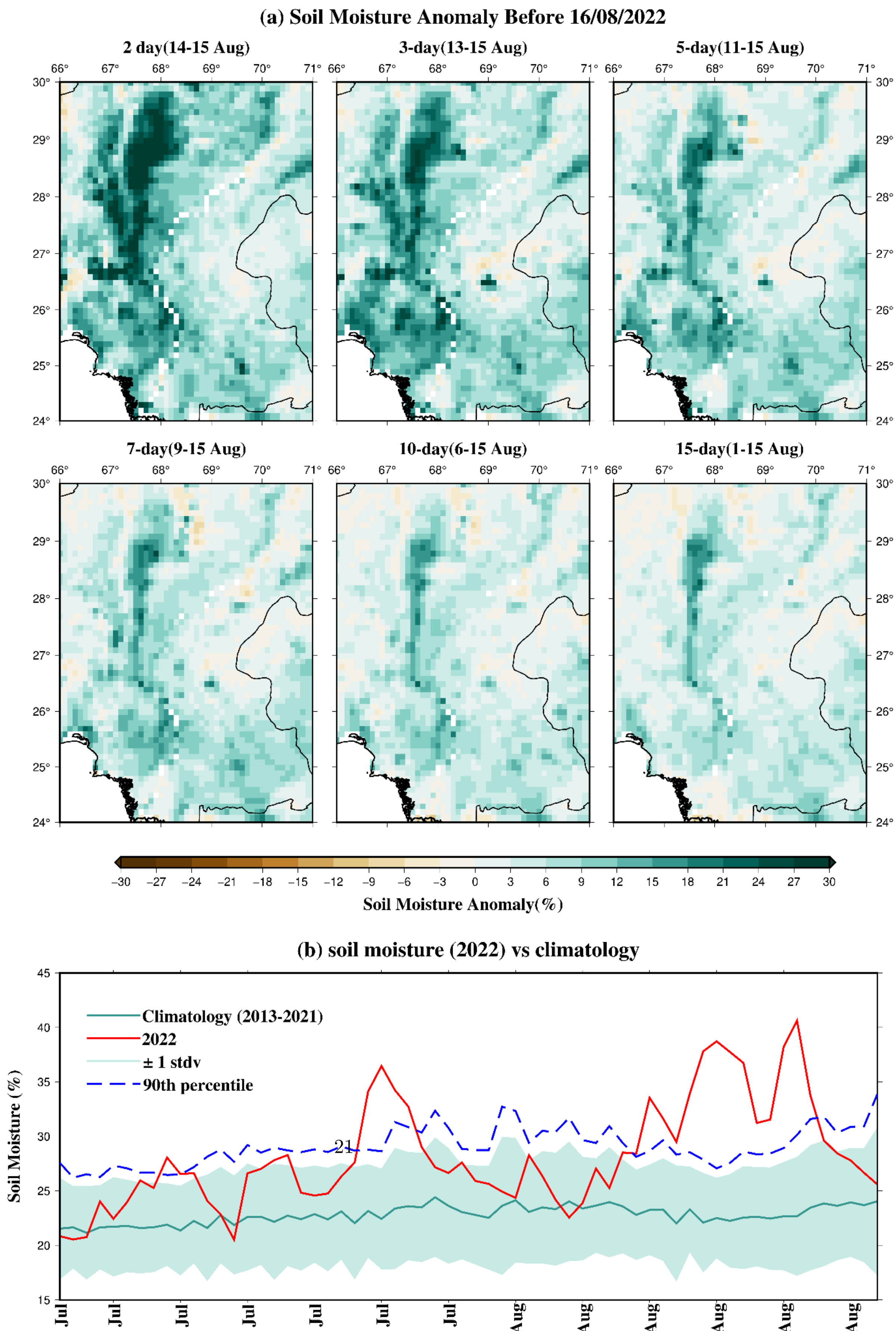
(a) Soil Moisture Anomaly Before 16/08/2022
2 day(14-15 Aug)
3-day(13-15 Aug)
5-day(11-15 Aug)
7-day(9-15 Aug)
10-day(6-15 Aug)
15-day(1-15 Aug)
66° 67° 68° 69° 70° 71°
30° 29° 28° 27° 26° 25° 24°
−30 −27 −24 −21 −18 −15 −12 −9 −6 −3 0 3 6 9 12 15 18 21 24 27 30
Soil Moisture Anomaly(%)
(b) soil moisture (2022) vs climatology
Climatology (2013-2021)
2022
± 1 stdv
90th percentile
Soil Moisture (%)
45 40 35 30 25 20 15
Jul
Jul
Jul
Jul
Jul
Jul
Jul
Aug
Aug
Aug
Aug
Aug
Aug

Figure 3. Spatial distribution of multiday mean soil moisture on 15 August 2022. The spatial plots show the soil moisture anomaly on 15th August2022 estimated at different durations from 2 to 15 days with reference to mean calendar day soil moisture from 2013 to 2021. The temporal plot shows daily soil moisture evolution for the study area from 1 July to 31 August. The 90th percentile of soil moisture and the mean and standard deviation of soil moisture from 2013 to 2021 for the same calendar days are shown in the figure. We used volumetric soil moisture data from LPRM from 2013-2022 for the analysis.

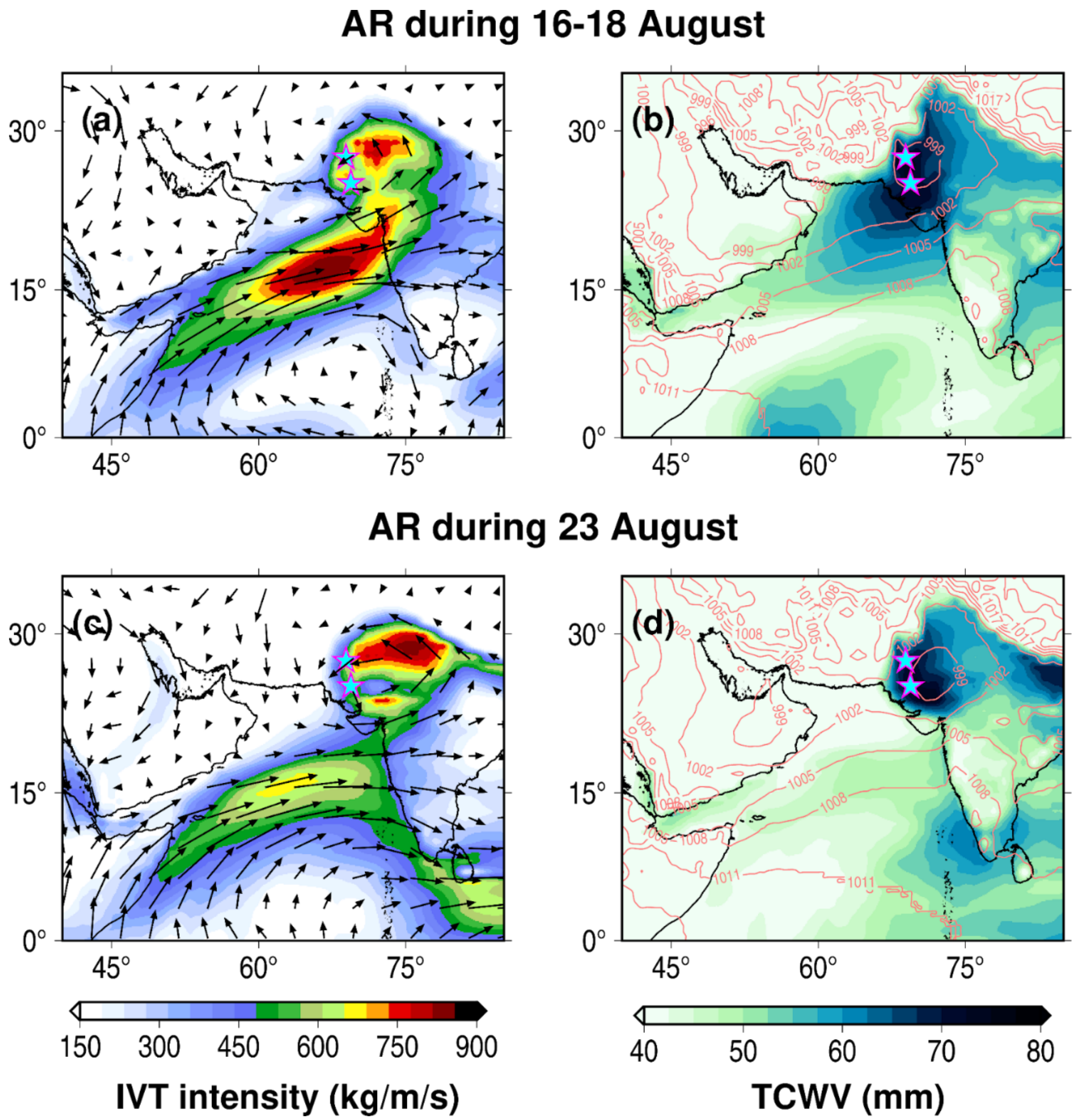

Figure 4. Atmospheric river (AR) during August 2022 flood in pakistan. (a) Vertically integrated moisture transport (IVT, kg/m/s) and (b) total column water vapour (TCWV, mm) in the presence of AR during 16-18 August 2022. (c-d) Same as (a-b) but for AR during 23 August 2022. The contours in (b) and (d) show the isobars in hPa.

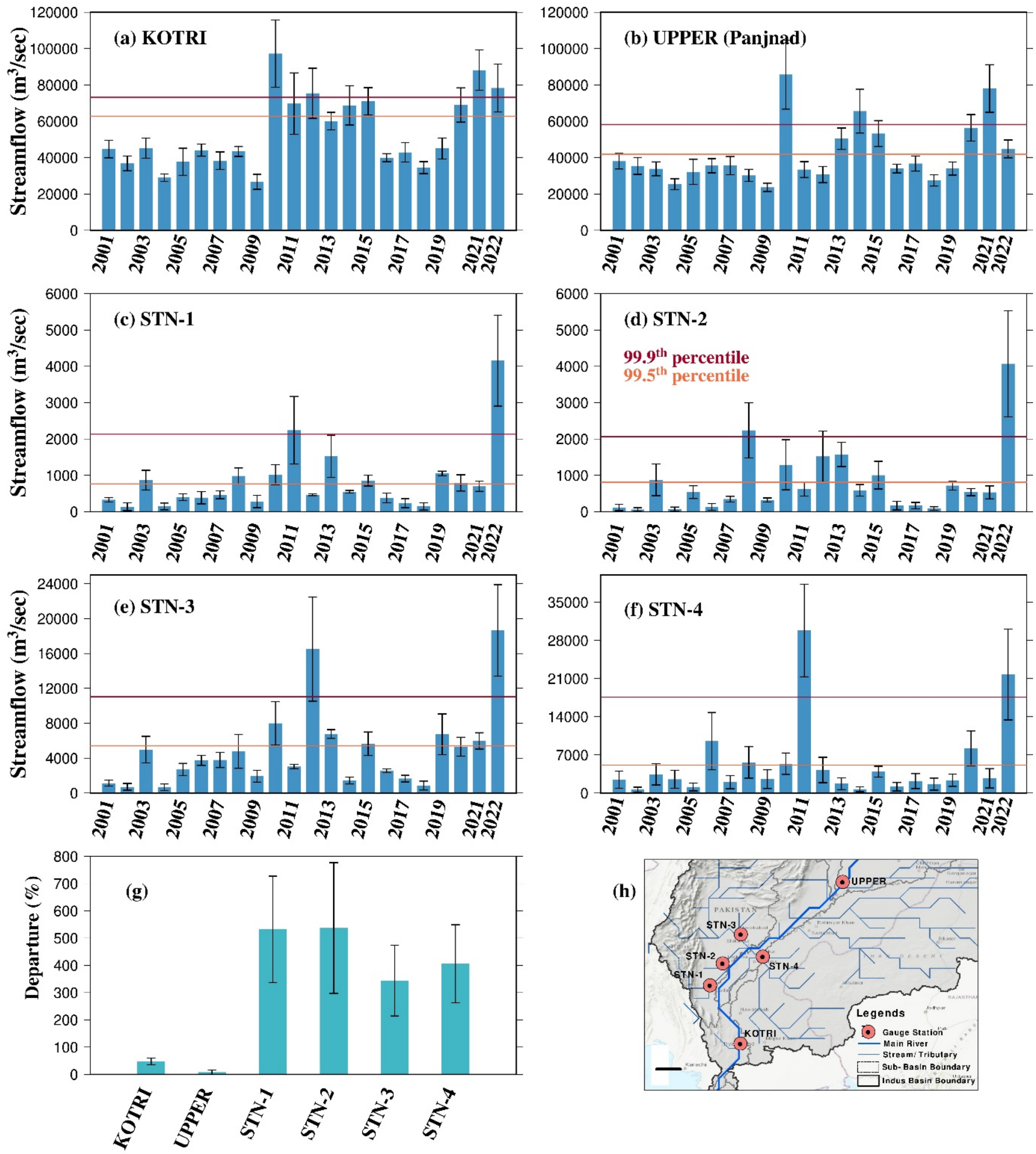

Figure 5. Ensemble streamflow simulations from four hydrological models (VIC, CLM, NOAH-MP and H08) at six different locations along the Indus basin,

which includes one station each at the (a) downstream (Kotri) and (b) upstream (Panjanad) point of the flood affected region and (c-g) four stations on either side of the Indus river. Figures (5 a-f) show the annual maximum flow from 2001 to 2022. The 99.9th and 99.5th thresholds of annual maximum streamflow from 2001-2021 is denoted in the figure. Figure 5-g depicts the percentage departure of the ensemble mean of annual maximum streamflow in 2022 at six stations. Whiskers indicate the uncertainty in the ensemble streamflow prediction. Figure 5h shows the location of all the six stations within the Indus basin.

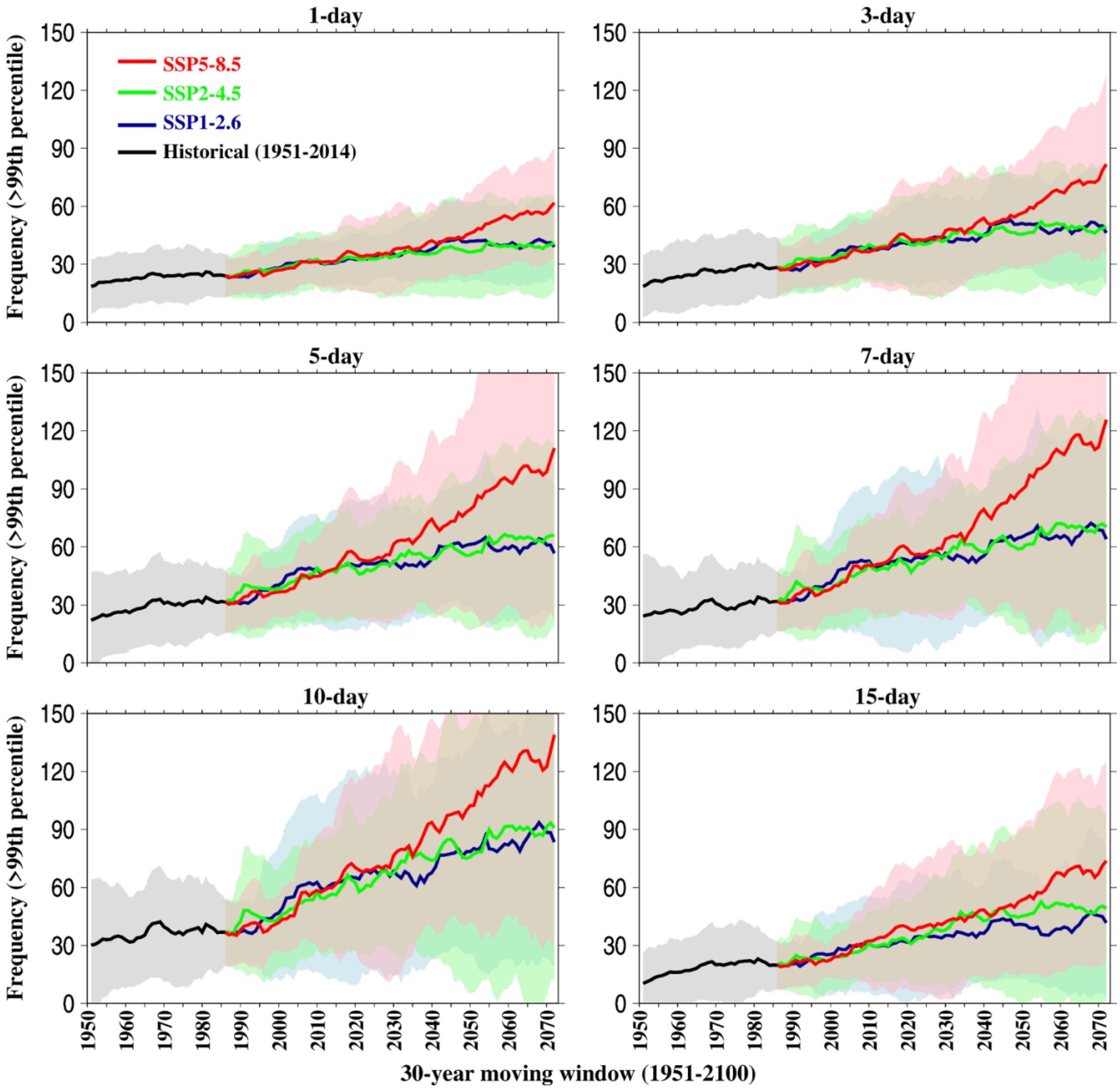

Figure 6. The multi-model ensemble mean frequency of precipitation exceeding 99^{th} percentile of rainy days (>0.2mm per day) for the historical (1950-2014; with pre-industrial forcing) and future period (2015-2100; includes anthropogenic greenhouse gases) for 1-day, 3-day, 5day, 7day, 10-day and 15-day accumulated precipitation, and for three warming scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5). The period 2001-2014 was selected as the reference period to estimate the 99^{th} percentile value for the nine CMIP6-GCMs. The frequency is estimated using a 30-day moving window. Shading represents the standard deviation for each emission scenario.