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Increased flood risk in South Asia under warming climate

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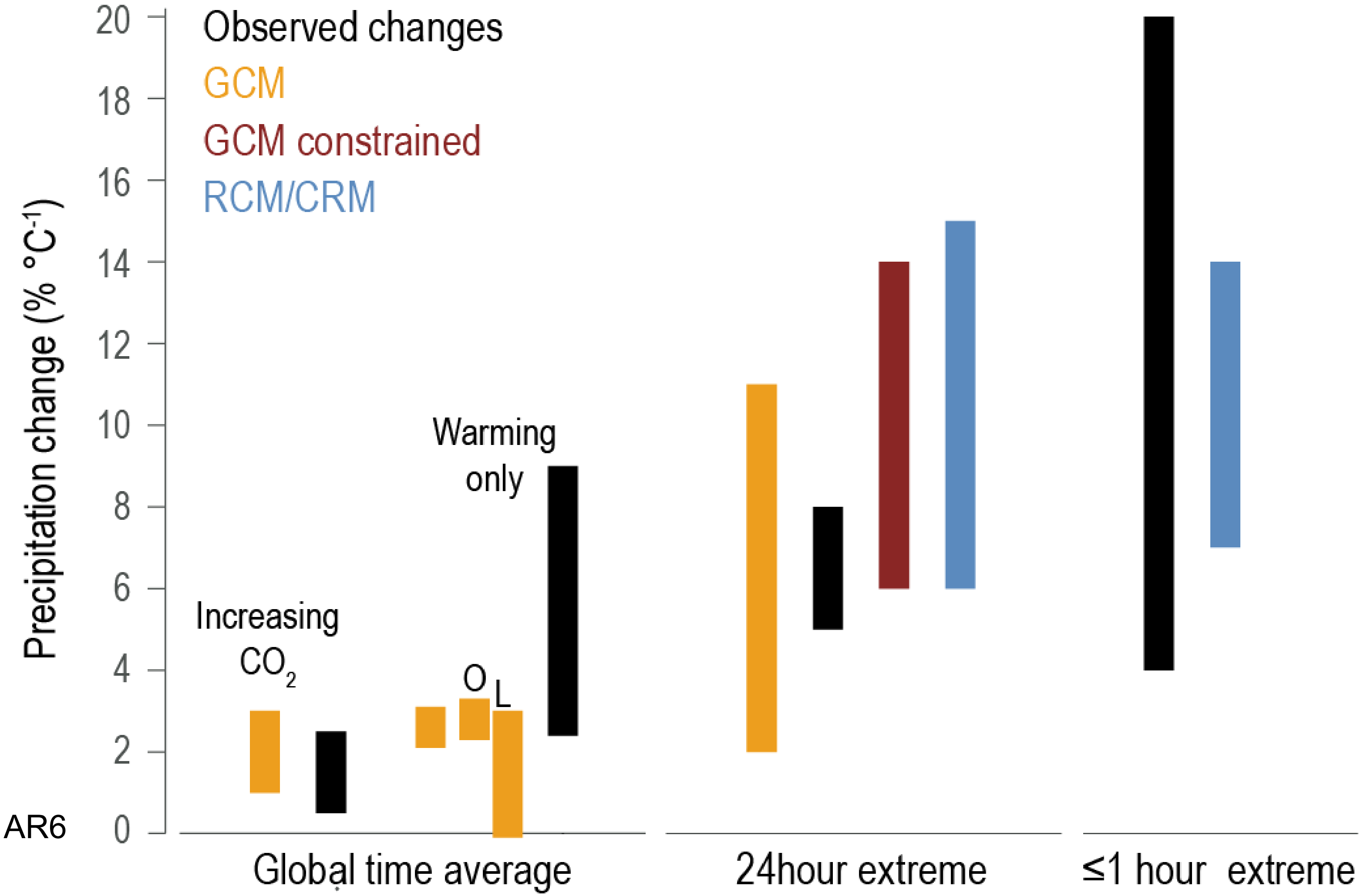
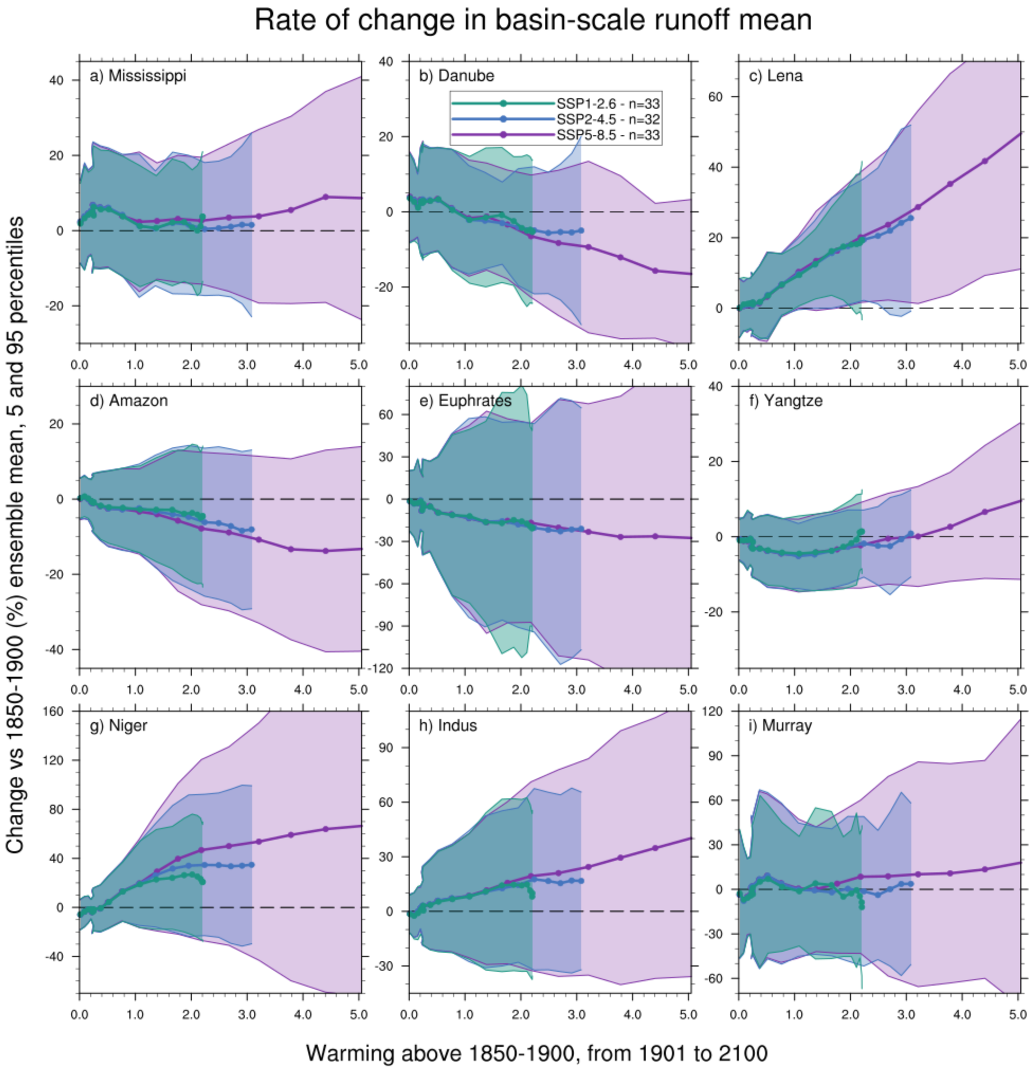

Observed changes
GCM
GCM constrained
RCM/CRM
Precipitation change (% °C-1)
20
18
16
14
12
10
8
6
4
2
0
Warming only
Increasing CO2
O
L
Global time average
24hour extreme
≤1 hour extreme

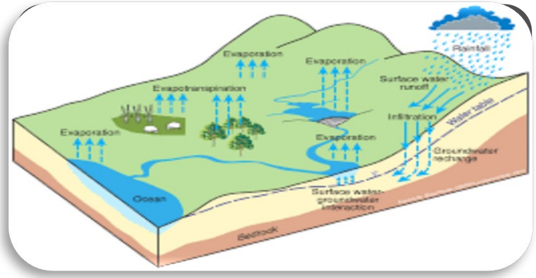
IPCC AR6

Rate of change in basin-scale annual mean runoff with increasing global warming levels



IPCC AR6-WG1

The drivers of floods



The intensity and duration of precipitation.

Amount and source of moisture.

Direction of movement.

Intensity of associated low-pressure systems.

Antecedent soil moisture.

Catchment area

Stream density

Evapotranspiration

Soil and land-use characteristics

Surface and sub-surface flow

River training works

Reservoirs

Levees

River cross-sections

Channel processes

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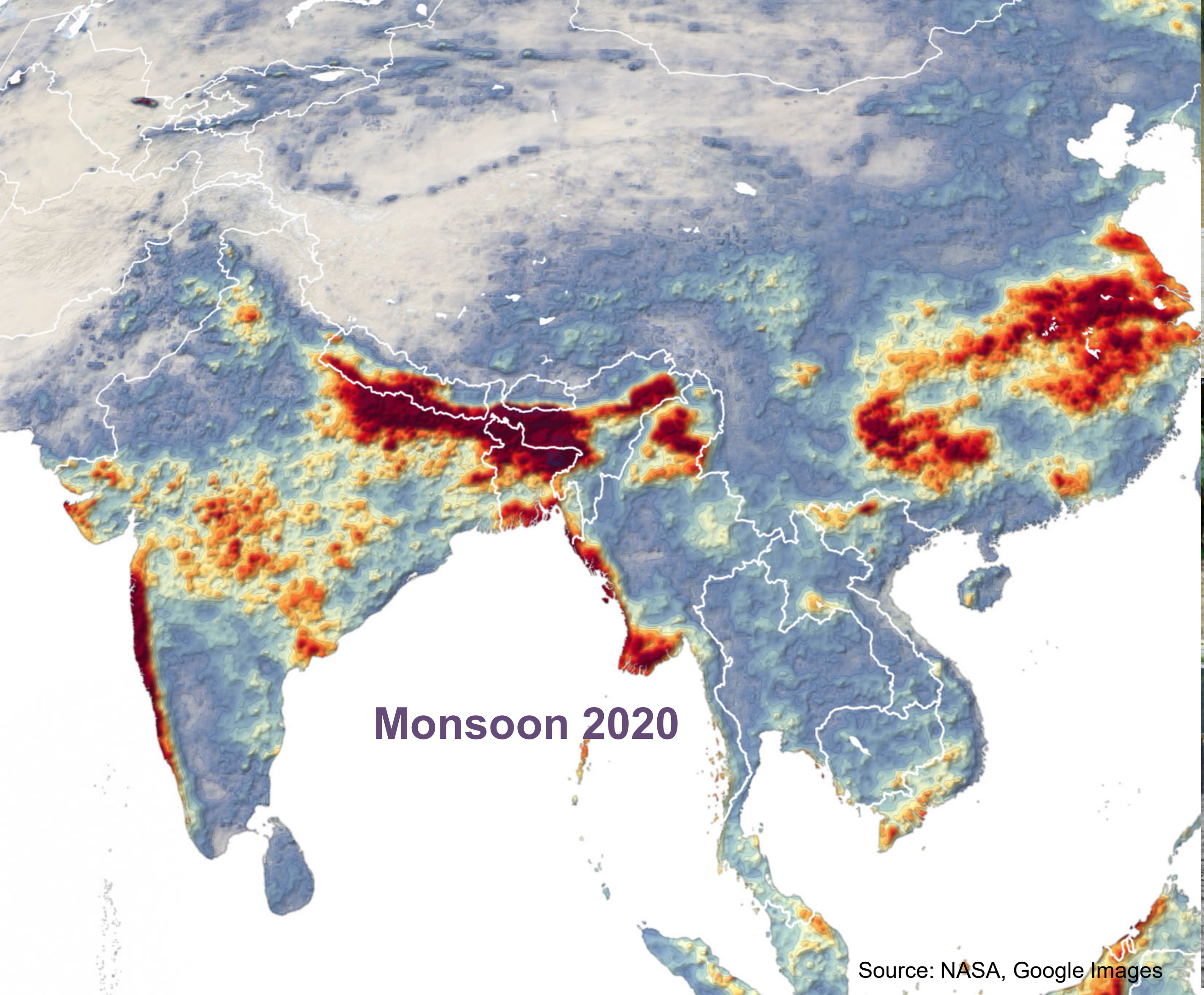
Monsoon 2020



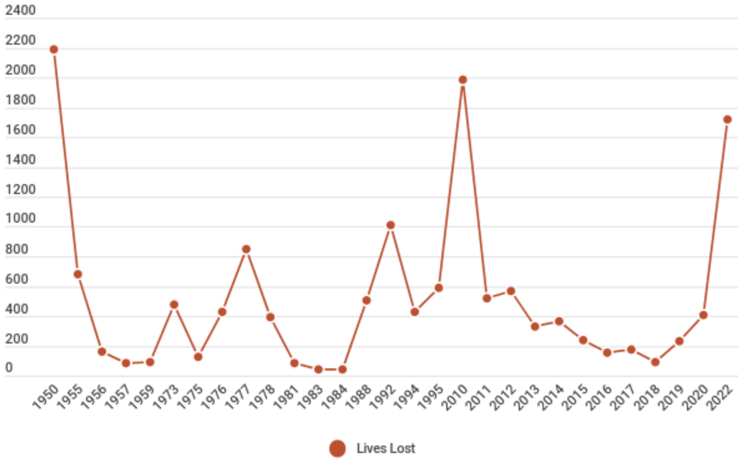
Source: NASA, Google Images

The Pakistan flood: 2022

A displaced family wades through a flooded area in Jafarabad, a district of Pakistan's southwestern Baluchistan province, on Aug. 24. (Zahid Hussain/AP)

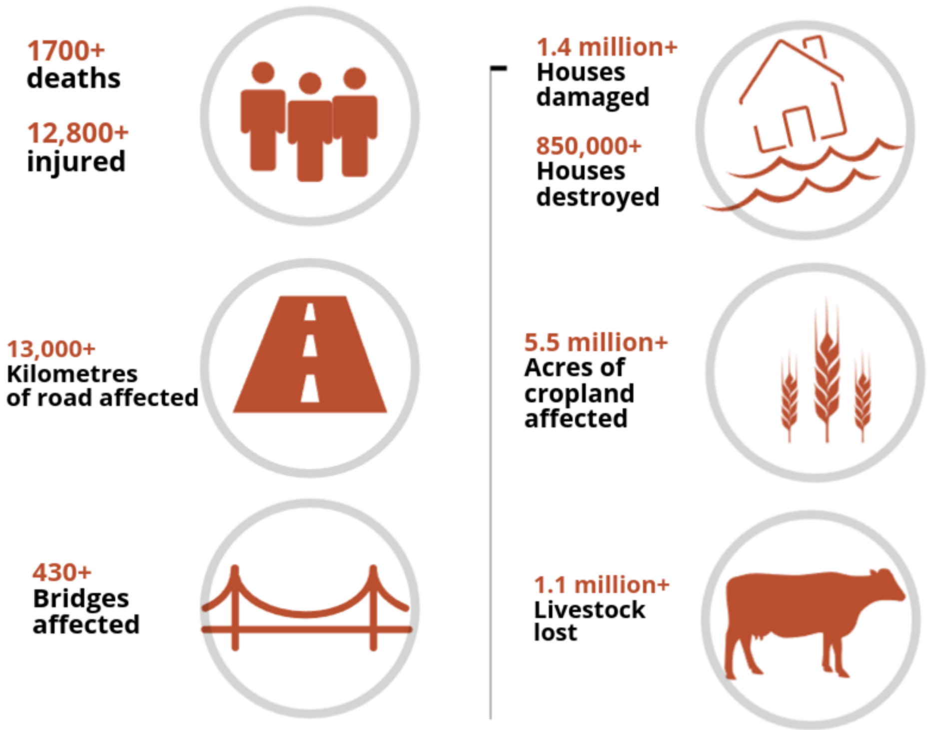
Source: Washingtonpost

Pakistan Flood Fatalities between 1950-2022

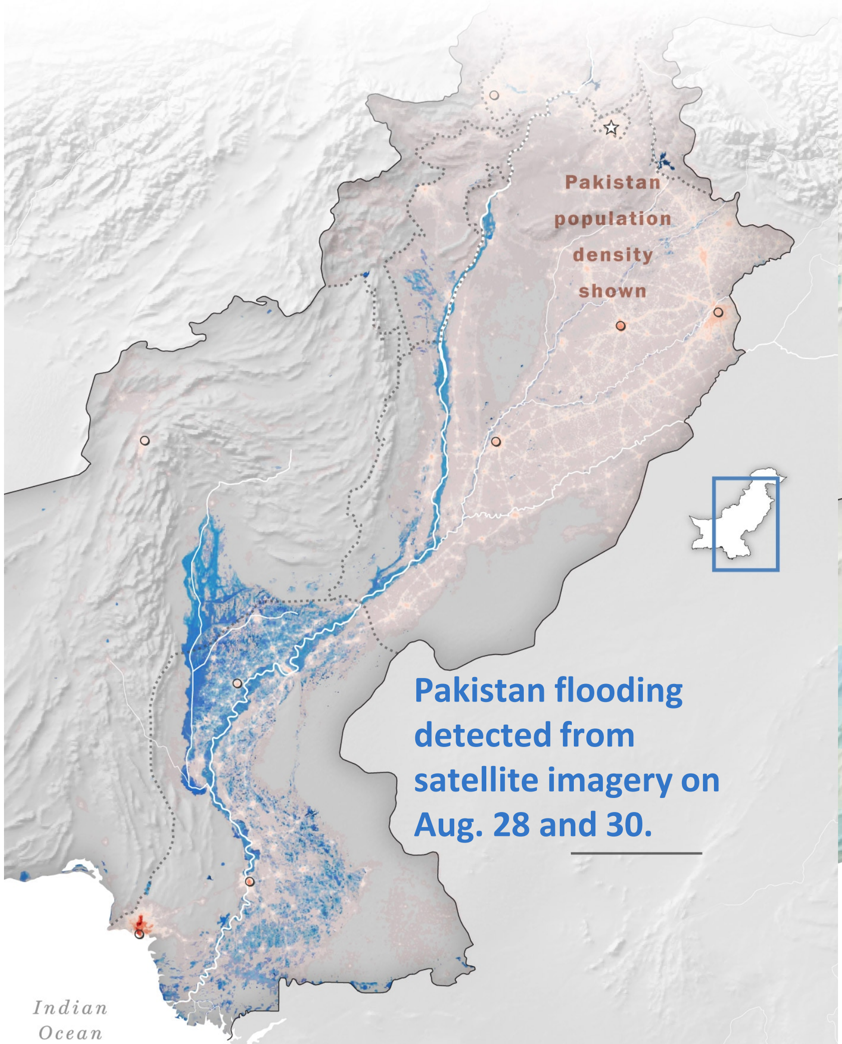


Data Source: Government of Pakistan Ministry of Water Resources

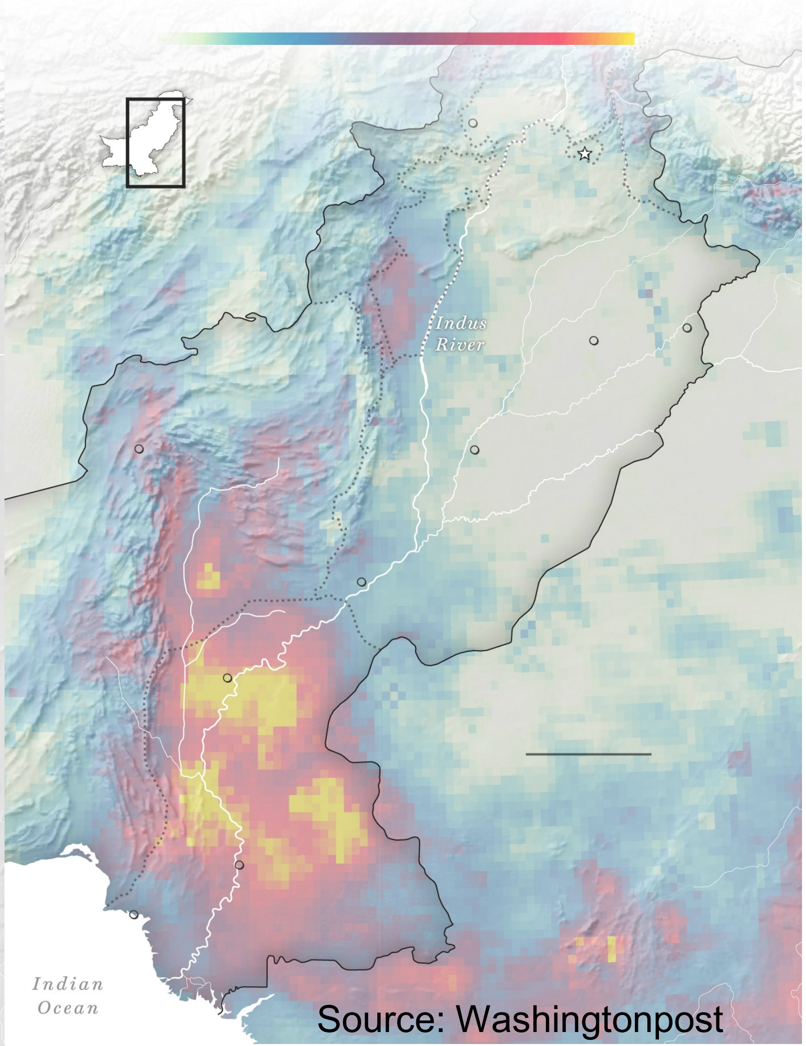
Damages caused by 2022 Pakistan flood



Source: National Disaster Management Authority (NDMA), Government of Pakistan 19 October 2022 & Pakistan food security and Agriculture 5 October 2022



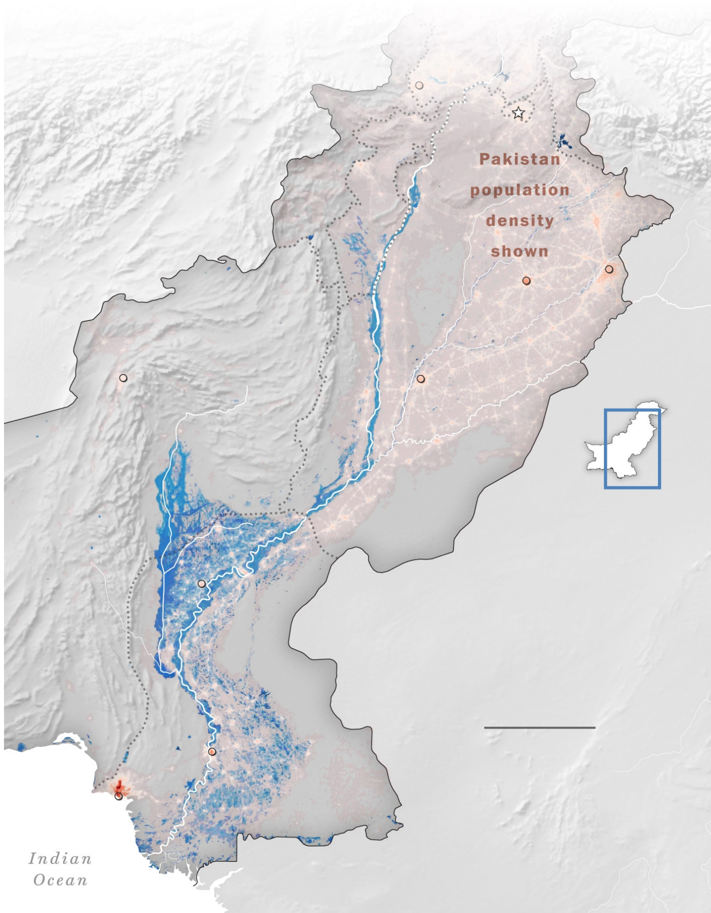
Pakistan flooding detected from satellite imagery on Aug. 28 and 30.



Source: Washingtonpost

Rainfall Departures during the summer monsoon, 2022

- National rainfall for the month of June 2022 was largely **(+68%)** above normal. Balochistan **(+47.6%)** an Sindh **(-14%)**
- National rainfall for the month of July 2022 was largely **(+180%)** above average and stands as record wettest July since 1961.
- July 2022 rainfall was excessively above average over Balochistan (+450%) & Sindh (+307%), both rank as the wettest ever during past 62 years.
- National rainfall for the month of **August 2022 was excessively (+243%)** above average and stands as record wettest August since 1961.
- August 2022 rainfall was excessively above average over Balochistan (+590%) & Sindh (+726%)
- National rainfall for the month of September 2022 was below average (-21%).

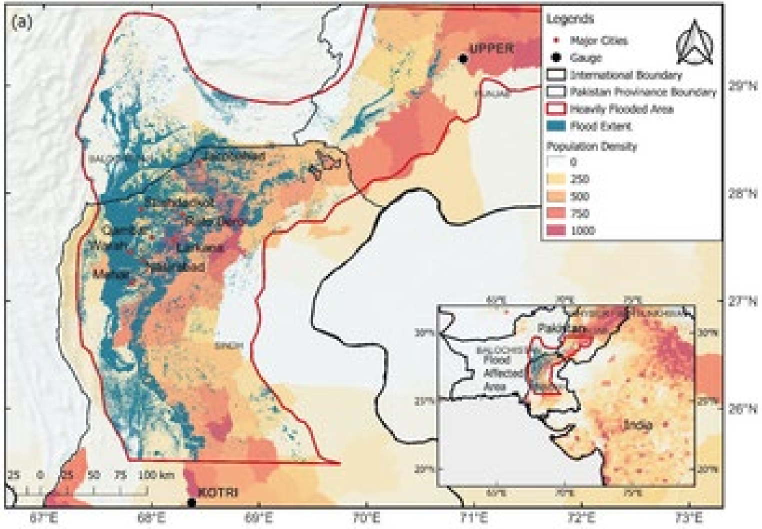


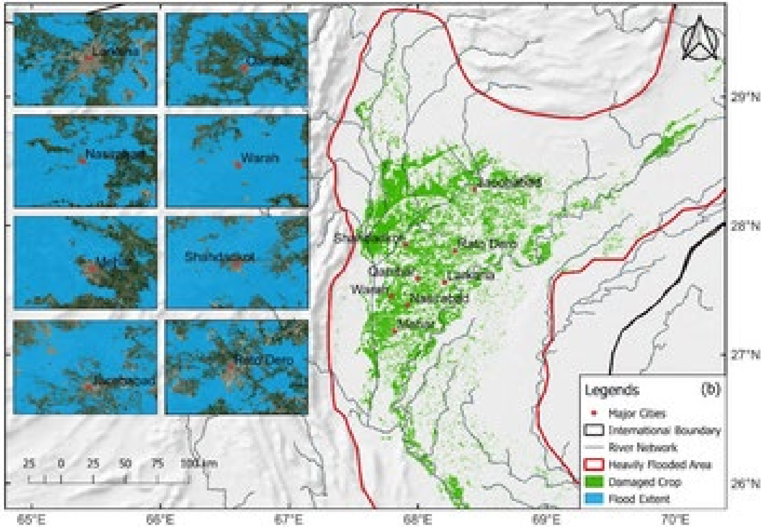
The 2022 flood event in the context of the top 20 flood events in Pakistan that led to the death of more than 100 people.

Sl. No.	Year	Area (km^2)	Dead	Displaced	Major cause	Severity	Other affected countrie
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

Flood Extent

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. The shading on 1(a) shows the population density (number of people/km^2) obtained from SEDAC (refer Table S1 in Supporting Information S1). 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. Panel (b) shows the crop areas affected during the 2022 flood vent. The crop data is obtained from Sentinel-2 based ESRI LULC classification at 10 m spatial resolution. The inset figures, generated using sentinel-2, depict flood inundation in major cities.





Extreme Rainfall Analysis

- We analyzed the deviation of rainfall in 2022 august to its climatology to identify the main period of extreme rainfall

- Using accumulated rainfall, we identify the most affected regions exceeding 400 mm rainfall for 15 accumulated days over Pakistan.

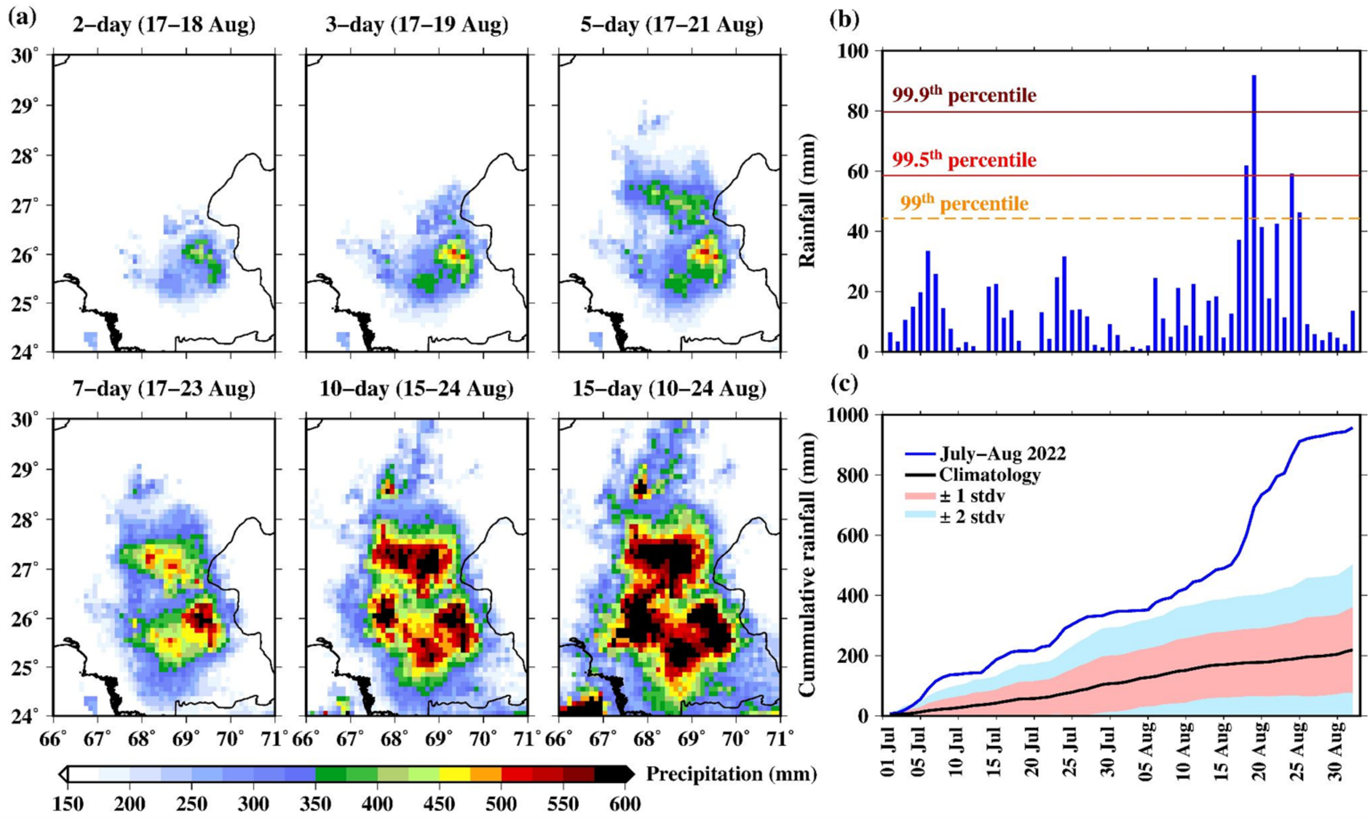
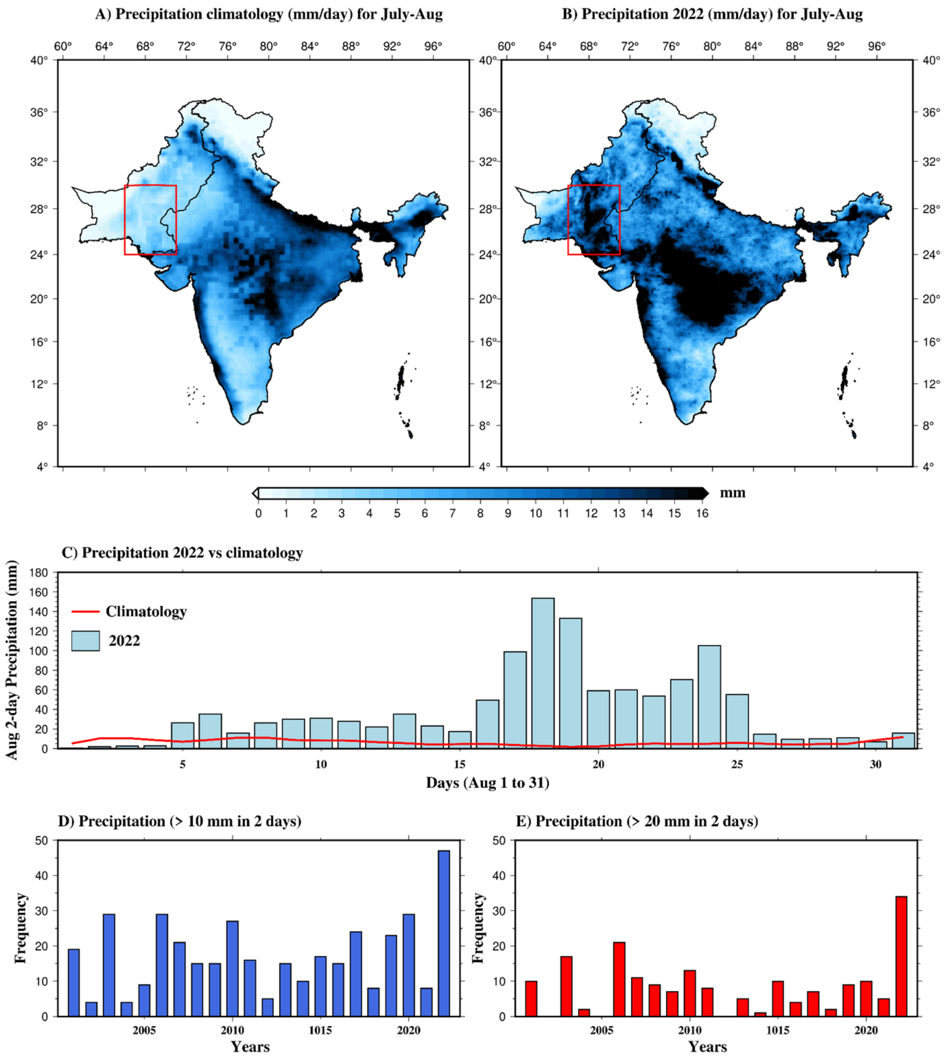


Figure 2. Precipitation extent during the 2022 flood in Pakistan. (a) Multi-day maximum accumulated precipitation during July-August 2022. (b) Observed daily precipitation (mm) over the affected area (continuous grids having 15-day maximum precipitation >400mm). (c) Cumulative rainfall from 1 June to 31 August 2022 (blue) and its climatology (black) for the affected area. The shaded region show the 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.

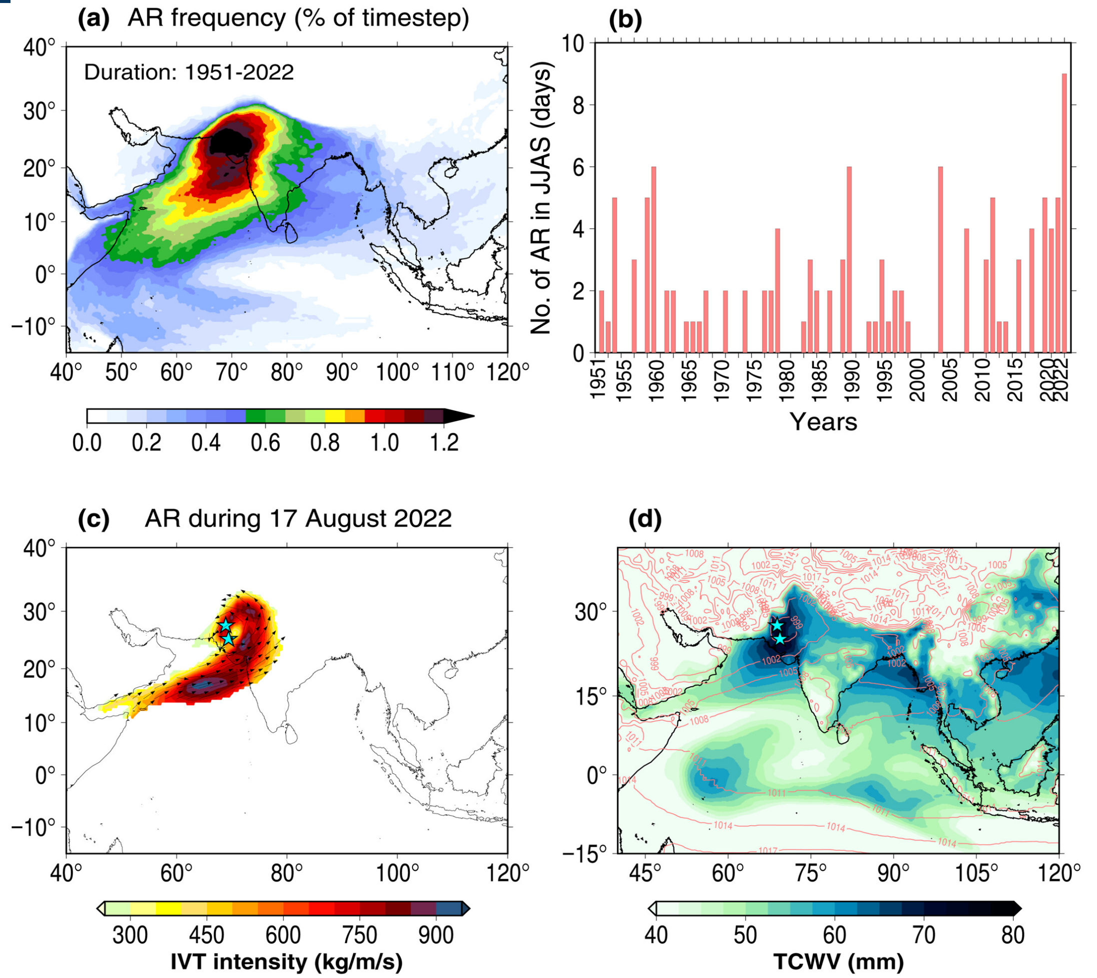


- **Extremely anomalous rainfall in August 2022 over Pakistan**
- **Highest number of days exceeding >=10 mm and 20 mm rainfall in 2022 July-August.**

(a) July-August GPM precipitation [mm/day] climatology for 2003–2021. (b) The observed GPM rainfall averaged for Pakistan (60°N–76°N; 24°E–30°E, red rectangle). (c) 2-day accumulated rainfall of climatology over the selected red region in August 2022. (d) Frequency of two days accumulated rainfall of 10 mm and (e) 20 mm over Pakistan (66°N–76°N; 24°E–30°E).

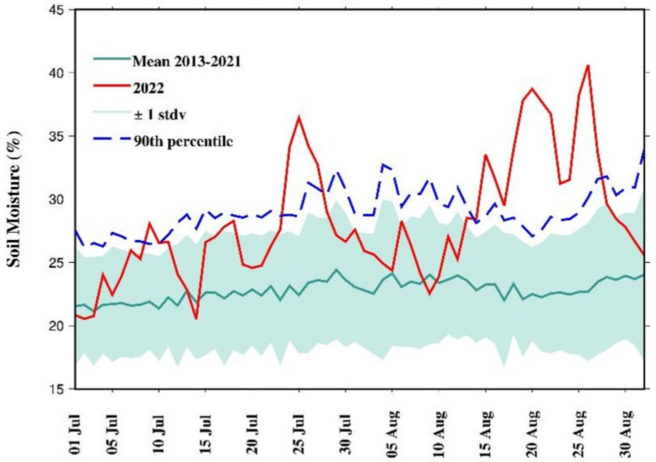
Role of Atmospheric Rivers

Atmospheric river (AR) during August 2022 flood in Pakistan. (a) Frequency of occurrence of AR (% of time-step) in each grid cell in the monsoon season (JJAS, June–September) over Pakistan region (23–33°N, 63–73°E). (b) Number of ARs each year in JJAS. (c) Vertically integrated moisture transport (IVT, kg/m/s) and (d) total column water vapor (mm) in the presence of AR during 17th August 2022. The arrows in (c) show the IVT direction during the AR. The contours in (d) show the isobars in hPa. The IVT intensity in (c) shown only for the AR grids, identified using AR identification criteria developed from Guan and Waliser (2015) and Pan and Lu (2020). See Section 2.4 for details.



Soil Moisture Conditions during flood

We estimated 2-15 day mean soil moisture anomaly on 15 August using the volumetric soil moisture percentile observations from 2013-2022.



Advanced Microwave Scanning Radiometer 2 (AMSR2) and Land Parameter Retrieval Model (LPRM)

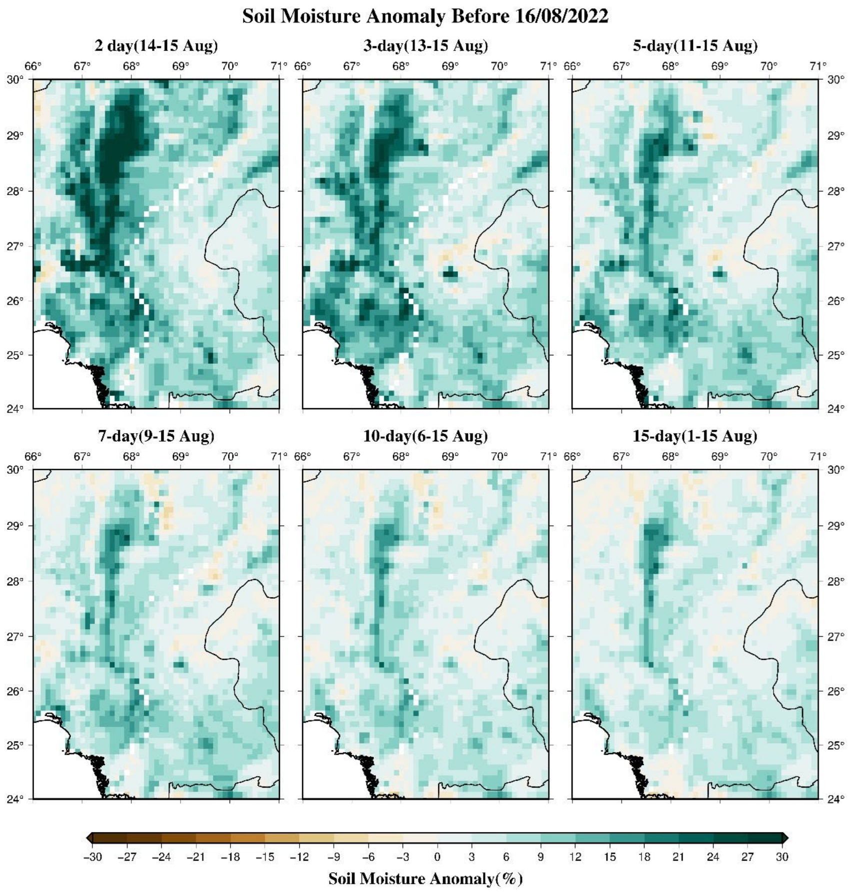


Figure 4. Spatial distribution of multi-day mean soil moisture on 15 August 2022. The spatial plots show the soil moisture anomaly on 15th August 2022 estimated at different durations from 2 to 15 days with reference to mean calendar day soil moisture from 2013 to 2021. The temporal plot shows daily soil moisture evolution for the study area from 1 July to 31 August.

Streamflow simulations of the 2022 flood event

- All stations exceeds the 99.9th percentile threshold of the 2001-2021 annual maximum discharge time series, except in the upstream station, Panjanad. Similarly, the percentage streamflow departure.

- Extreme precipitation (16-24 August) along with wet antecedent soil moisture conditions translated to higher streamflow values at the four locations.

- Contribution from the upstream reaches of the Indus basin to the observed August flooding is less significant.

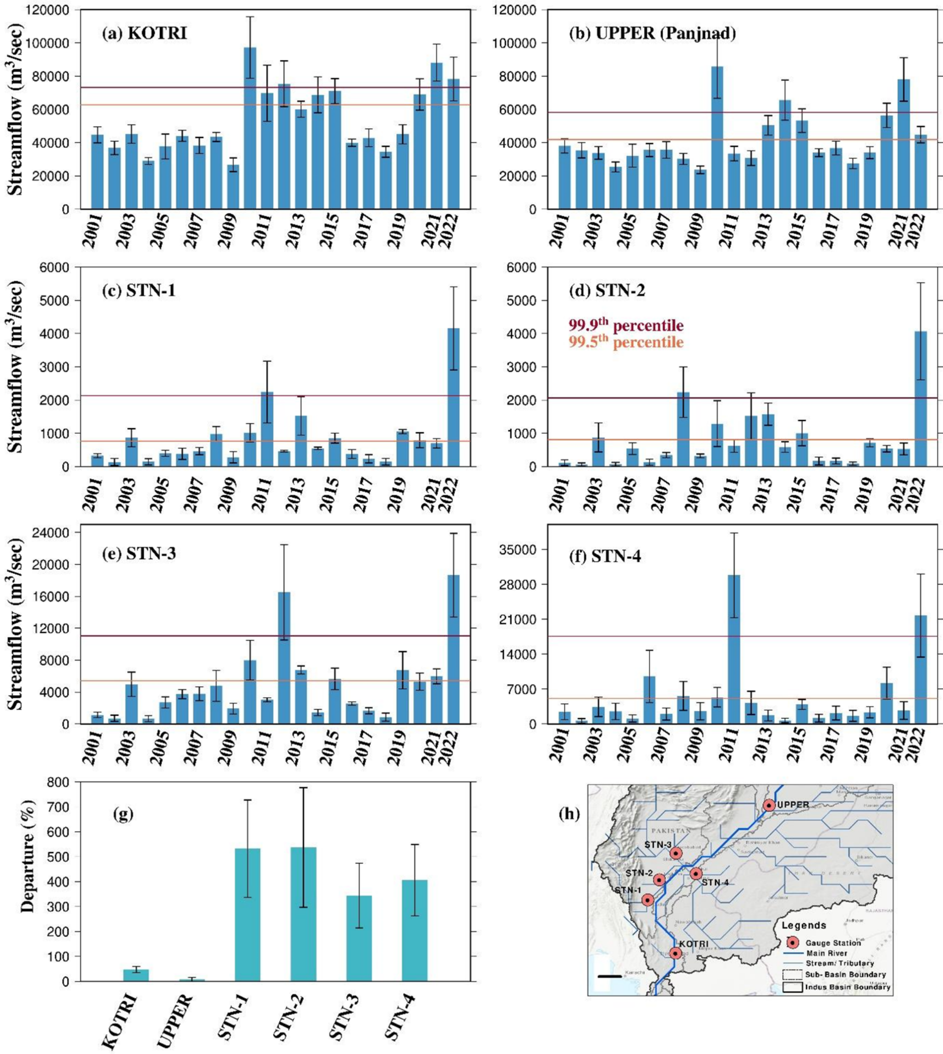


Figure 6. Ensemble streamflow simulations from four hydrological models (VIC, CLM, NOAH-MP and H08) at six different locations along the Indus basin, which includes one station each at the (a) downstream (Kotri) and (b) upstream (Panjanad) point of the flood affected region and (c-g) four stations on 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.

Future projections of extreme precipitation events

- The frequency of extreme precipitation is projected to rise in all the warming scenarios.
- The frequency of seven-day and ten-day precipitation is projected to quadruple by the end of the 21st century in the SSP5-8.5 scenario.
- Multiday precipitation encompasses extreme precipitation and antecedent soil moisture conditions and is more likely to translate to floods.

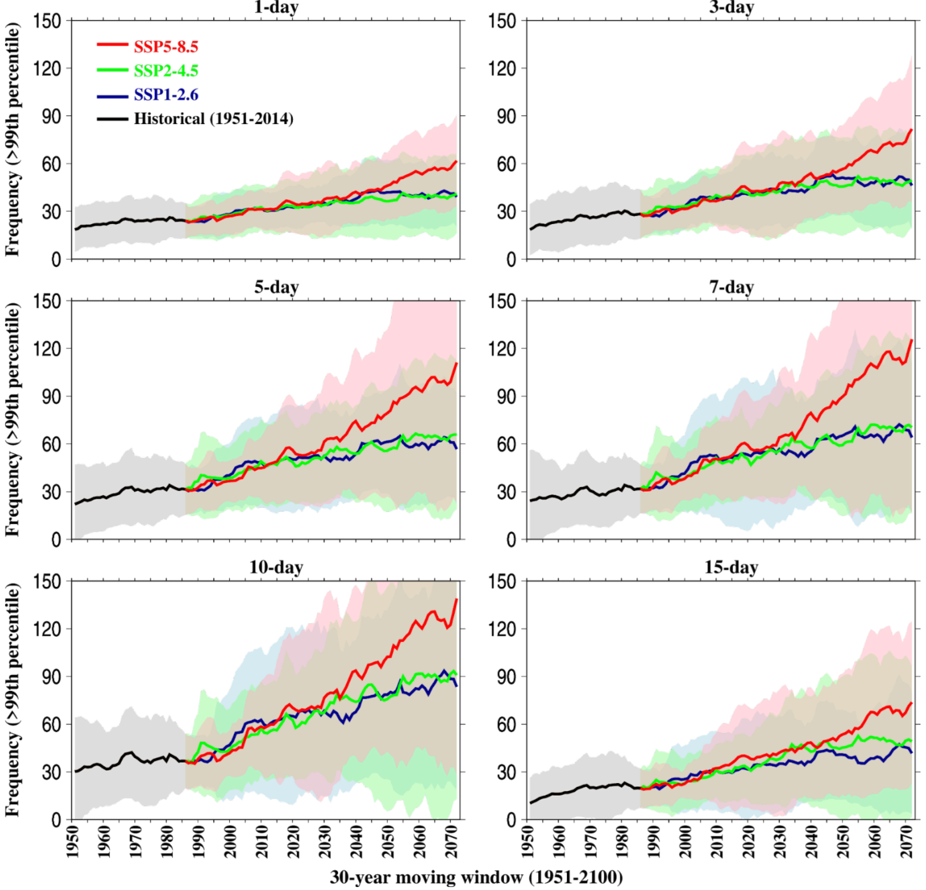
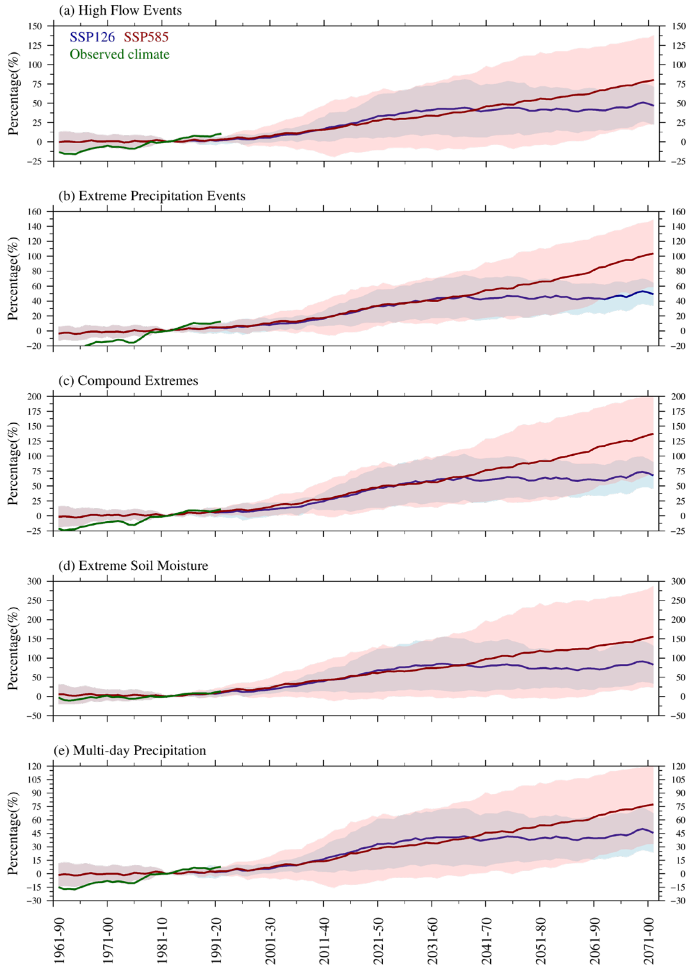


Figure 7. The multi-model ensemble mean frequency of precipitation exceeding 99th percentile of rainy days (>0.2mm per day) for the historical (1950-2014; with pre-industrial forcing) and future period (2015-2100; includes anthropogenic greenhouse gases) for 1-day, 3-day, 5day, 7day, 10-day and 15-day 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 99th 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.

Future changes in floods and their drivers



Percentage increase in the frequency of extreme events in a 30-year moving window with respect to 1981-2010 reference period. (a) high flow events and (b) extreme precipitation events, (c) compound extremes, (d) extreme soil moisture events and (e) multi-day precipitation events preceding high flow events in the SSP1-2.6 (blue) and SSP5-8.5 (red) scenarios

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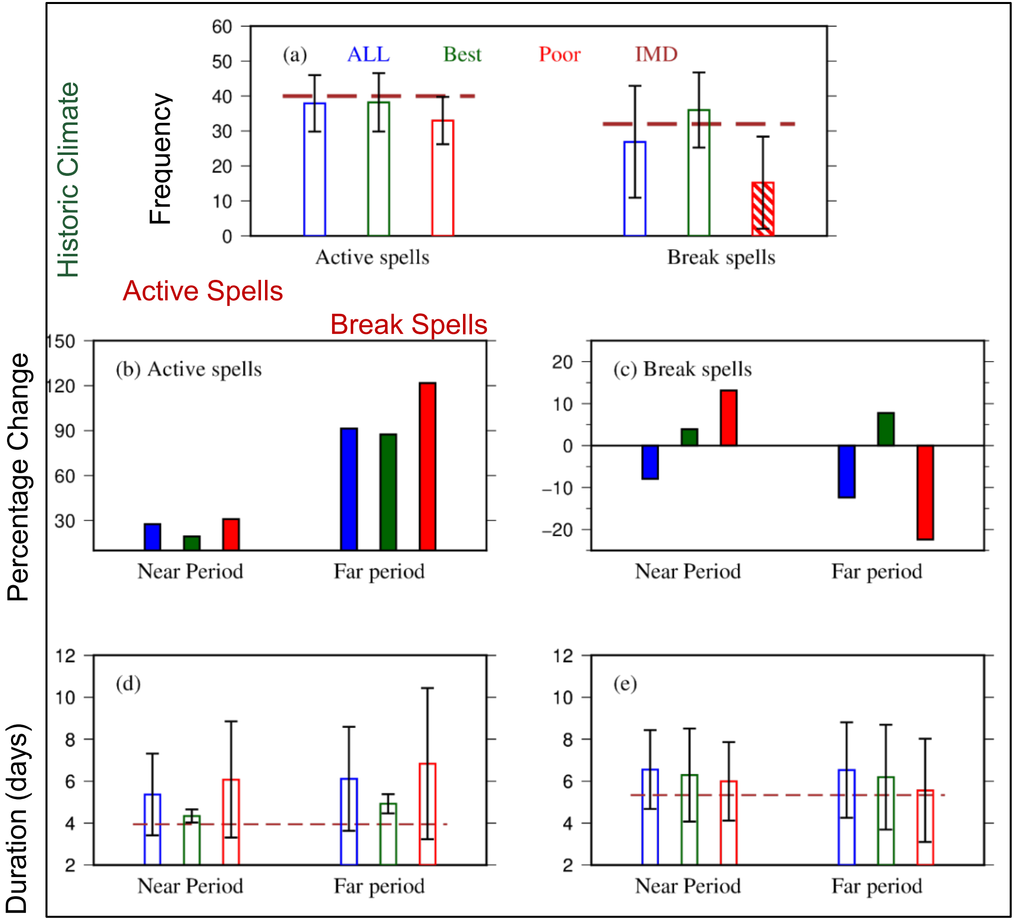
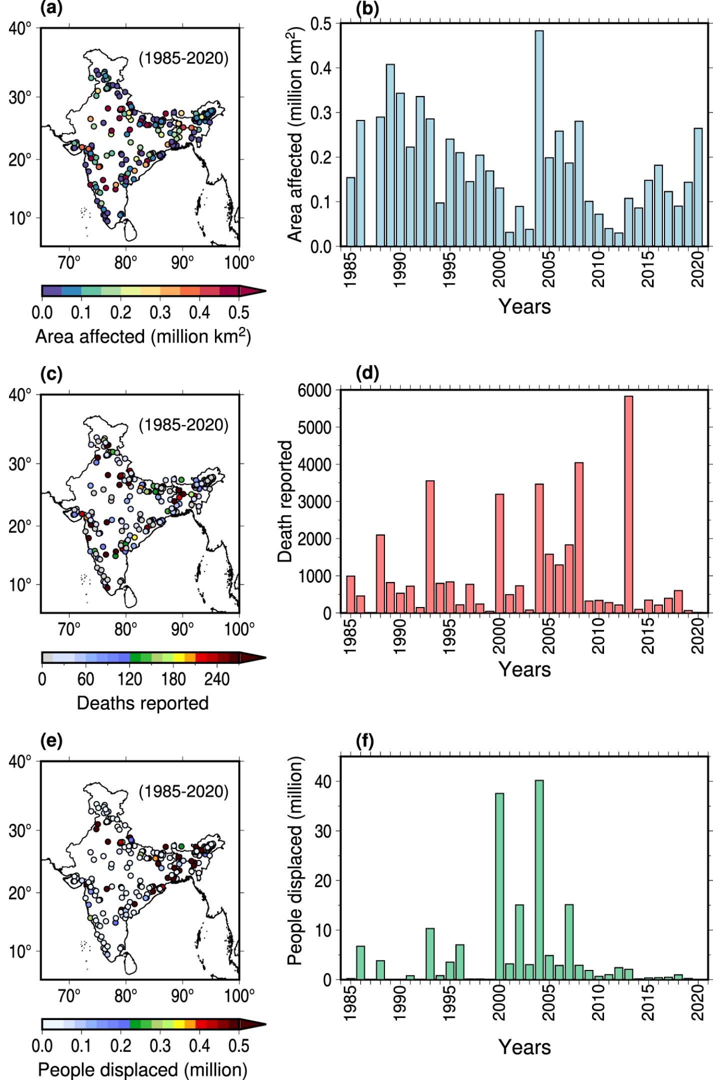
Active and Break Spells in a Warming Climate



- POOR GCMs underestimate the frequency of break spells during the reference period.
- Frequency of break spells projected to decrease in POOR and ALL GCMs

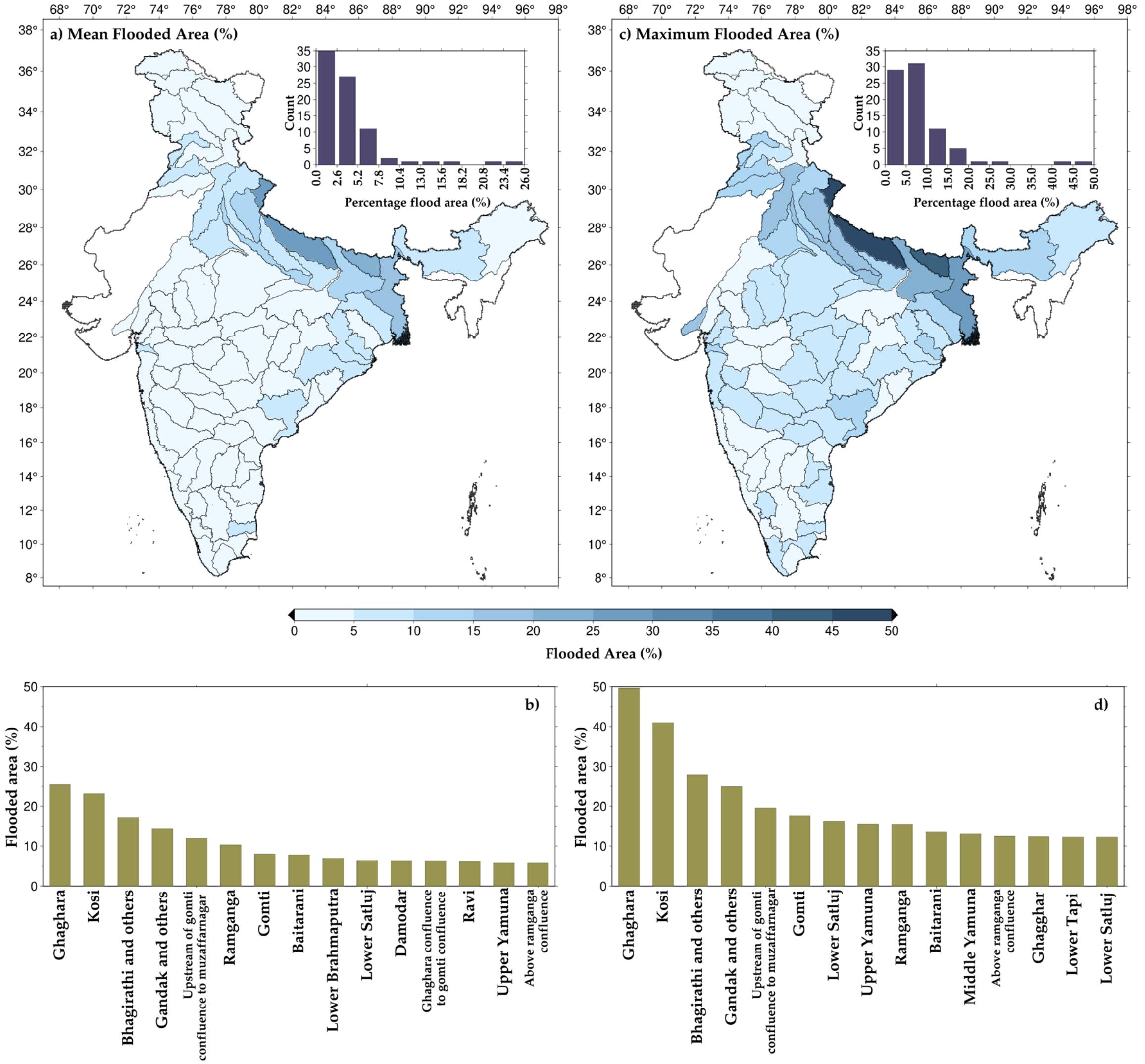
Major floods during the summer monsoon season (June-September) in India during 1985–2020



a Flood locations with color scale representing the total geographical area affected (in million km^2). **b** Average area affected by floods during 1985–2020. **c** Deaths reported due to the major floods along with their locations. **d** Total deaths reported each year during 1985–2020. **e** People displaced due to floods and their locations. **f** Total population displaced each year due to floods. The major flood data base was obtained from the Dartmouth Flood Observatory, University of Colorado, USA (available at https://floodobservatory.colorado.edu/Archives/index.html).

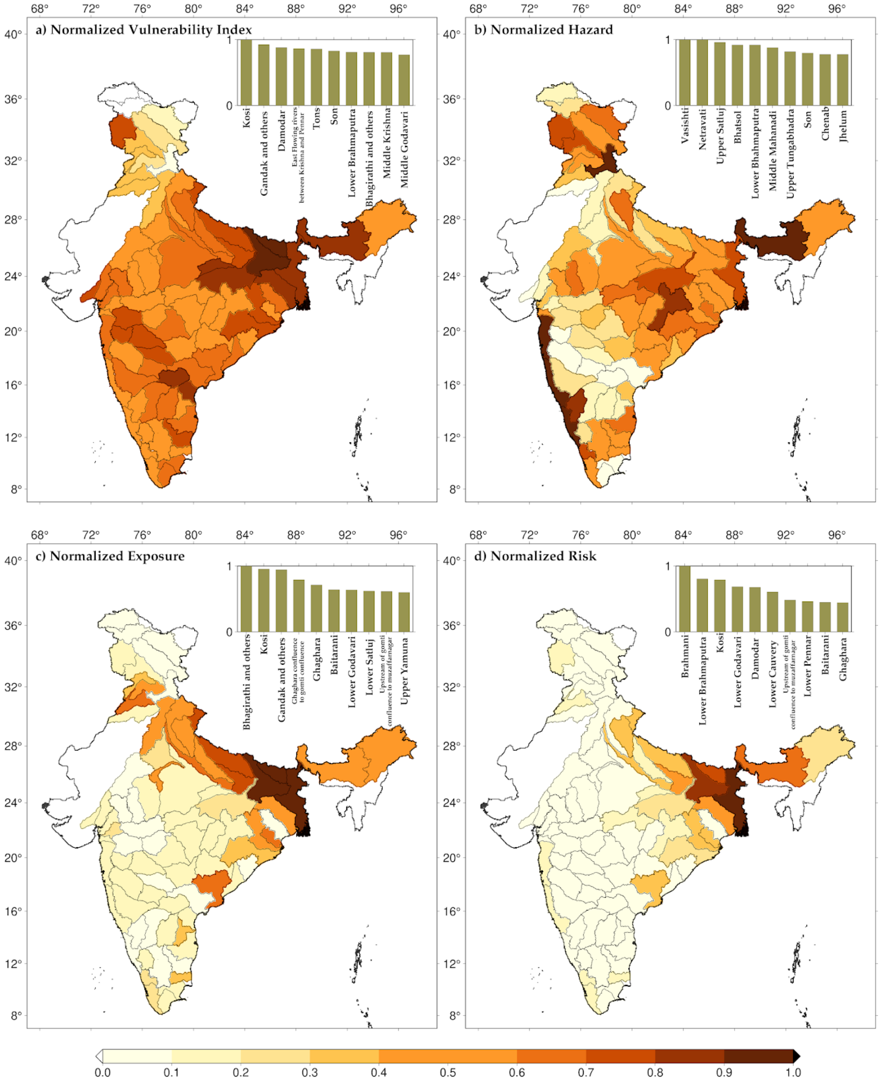
Flood risk assessment

(a) Mean of annual maximum flooded area (percentage) between 1901-2020 and the overall distribution (b) highlighting the top fifteen sub-basin. (c) Historical maximum flooded area (percentage) and the overall distribution (d) highlighting the top fifteen sub-basin.



Flood risk assessment

Sub-basin level (a) Normalized vulnerability index (b) Normalized hazard (c) Normalized exposure (d) Normalized risk. The top 10 sub-basins are highlighted as bars in panels inside the figures.



Conclusions

- 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
- South Asia would benefit from operational flood forecasting systems and early warning systems.
- Details flood risk assessment is needed considering the role of human intervention for climate change adaptation.

Thank you