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Climate change increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan

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Supplementary material for this article is available online

Abstract

As a direct consequence of extreme monsoon rainfall throughout the summer 2022 season Pakistan experienced the worst flooding in its history. We employ a probabilistic event attribution methodology as well as a detailed assessment of the dynamics to understand the role of climate change in this event. Many of the available state-of-the-art climate models struggle to simulate these rainfall characteristics. Those that pass our evaluation test generally show a much smaller change in likelihood and intensity of extreme rainfall than the trend we found in the observations. This discrepancy suggests that long-term variability, or processes that our evaluation may not capture, can play an important role, rendering it infeasible to quantify the overall role of human-induced climate change. However, the majority of models and observations we have analysed show that intense rainfall has become heavier as Pakistan has warmed. Some of these models suggest climate change could have increased the rainfall intensity up to 50%. The devastating impacts were also driven by the proximity of human settlements, infrastructure (homes, buildings, bridges), and agricultural land to flood plains, inadequate infrastructure, limited ex-ante risk reduction capacity, an outdated river management system, underlying vulnerabilities driven by high poverty rates and socioeconomic factors (e.g. gender, age, income, and education), and ongoing political and economic instability. Both current conditions and the potential further increase in extreme peaks in rainfall over Pakistan in light of anthropogenic climate change, highlight the urgent need to reduce vulnerability to extreme weather in Pakistan.

1. Introduction

From mid-June 2022, large areas of Pakistan experienced record-breaking monsoon rainfall, falling in several pulses, until late August. By the end of August large parts of the country were submerged. The Indus river, that runs the length of the country, burst its banks across thousands of square kilometres, while the intense rainfall also led to urban flash floods, landslides and Glacial Lake Outburst Floods (OCHA 2022a). Due to the Indus overflowing, a 100 km wide lake was created in the southern province of Sindh, which together with the neighbouring province of Balochistan constituted the worst affected region in the country. The record rainfall that fell between 1st and 31st August over Sindh and Balochistan was 726% and 590% of the usual totals for August (since 1961) in the respective regions (Business Recorder 2022). Pakistan as a whole received 243% more rainfall than usual during this period, and stands as record wettest August since records began in 1961 (PMD 2022). This exceptionally high monsoon precipitation hit a country with both high population density and high rates of poverty, creating significant vulnerability to climate-related hazards and potential changes in likelihood and intensity of such events. The flooding affected over 33 million people, destroyed 1.7 million homes, and nearly 1500 people died (NDMA 2022, VOA News 2022). On August 25th, the government declared a national emergency. Damages likely exceed preliminary estimates of around US$30 billion with further economic disruption certain in the months to come (Business Standard 2022). Around 6700 kilometres of road, 269 bridges and 1460 health facilities were destroyed (OCHA 2022b), 18 590 schools were damaged (Save the Children 2022), 750 000 livestock were killed (NDMA 2022) and around 18 000 square kilometres of cropland were ruined, including roughly 45% of the cotton crop (Bloomberg 2022a)—one of the nation's key exports. The loss of food crops, totalling around US$2.3 billion (Bloomberg 2022b), also compounds the ongoing food shortages due to the war in Ukraine and summer heatwaves in the region. There is also a severely heightened risk disease spreading, as stagnant flood waters provide a breeding ground for pathogens, and the vast number of people displaced results in poor hygiene and sanitation in temporary accommodation (Baqir *et al* 2012, Sarkar 2022). Notably, across Sindh and Balochistan, there has been an outbreak in waterborne disease such as diarrhoea and cholera, as well as skin and eye infections, malaria, and fever (IRC 2022).

Pakistan is one of the countries that are most at risk of climate extremes according to German Watch (2021) and has experienced several devastating floods, the last one on a similar scale to the 2022 event occurred in 2010. Pakistan is located at a place where two precipitation bearing weather systems terminate-the monsoon rains from east and southeast during summer, and the westerly disturbances from the Mediterranean Sea during winter. It is well established that climate change results in increasing the variability of these systems (Douville *et al* 2021). These changes, either spatially or temporally, make the country more prone to such extremes. Being a low-middle income country, Pakistan has low readiness despite its high vulnerability. The Notre Dame Global Adaptation index ranks Pakistan 32nd least ready country out of 181 to tackle climate change.

The country has a largely arid desert climate and frequently experiences severe heatwaves, such as the event in early summer 2022 that was strongly amplified by anthropogenic climate change (WWA 2022). It also periodically experiences destructive rainfall-induced flood events, as occurred in 2010. There is strong evidence of an increasing trend in extreme rainfall in South Asia (Seneviratne *et al* 2021) and an increasing strength and westward movement of the monsoon over Pakistan (Hanif *et al* 2013). However, there is low confidence that the observed extreme rainfall increase is due to human influence on the climate system (Seneviratne *et al* 2021), partially because other factors are known to influence monsoon strength and the level of impact, such as irrigation practices (Devanand *et al* 2019).

Previous attribution studies for the heavy rainfall of 2010 (responsible for massive flooding) have been undertaken, each using only a single model. Christidis *et al* (2013) found that the model used could not accurately reproduce such events. Meanwhile, Hirabayashi *et al* (2021) found an increase due to anthropogenic climate change, but the model was not assessed for its robustness in simulating monsoon dynamics. In a recent study, di Capua *et al* (2021) showed that the 2010 rainfall in Pakistan and the heatwave in Russia in the same year were connected by a wave train, which in turn was driven by sea surface temperature (SST) anomalies, soil moisture deficits in the extratropical regions and land surface warming in the high-latitudes. All or some of these drivers could be influenced by anthropogenic climate change, but whether and the extent to which this is the case remains highly uncertain. All of these studies thus underline the importance of (i) understanding the rainfall mechanisms and the factors that influence them including climate change, and (ii) the reliability of climate models in capturing them. Therefore, at present, there is overall low confidence in existing attribution findings for this region.

Meanwhile, climate projections indicate a rapid rise in the intensity of extreme precipitation events in the wider region including Pakistan with further global warming (Seneviratne *et al* 2021), linked to a stronger and more variable Indian monsoon (Katzenberger *et al* 2021, 2022). It is however important to highlight that these projections are conducted for a larger region including India, which has much less variable monsoon rains, and thus are not designed to specifically inform future changes in heavy rainfall over the region flooded in 2022.

In this study we answer the question whether and to what extent human induced climate change has altered the likelihood and intensity of the hazard, following primarily the probabilistic event attribution approach (Philip *et al* 2020) (section 3) but also exploring the influence of other drivers, including antecedent conditions and the role of La Niña thus bringing in elements of a storyline methodology (Shepherd *et al* 2018) (section 2). While a confluence of physical events was involved in the occurrence of this disaster, exposure and vulnerability of the people and communities impacted by the hazard played a huge role in both increasing and decreasing the impact of the extreme rain, which will be explored in section 4. Section 5 provides an overarching conclusion bringing these different drivers of the disaster together.

2. The 2022 Pakistan floods

2.1. The meteorological event

Pakistan is on the far western edge of the South Asian monsoon region, with a mostly arid desert climate in the southern provinces and humid to the north (Ahmed *et al* 2019). From June–September, Pakistan often receives heavy rainfall, especially in the northern parts of the country, with over half a million people affected by flooding annually (Baqir *et al* 2012). However, it is usually not affected by monsoon low pressure systems, and generally receives far less rainfall than parts of India at the same latitudes. As a result, precipitation rates in Pakistan are extremely variable (Ali *et al* 2020b, Adnan *et al* 2021). Past intense monsoons in both India and Pakistan are linked to strong La Niña events (Ju and Slingo 1995, Safdar *et al* 2019). In the supplementary material section S1 we provide additional details describing flood-producing mechanisms in Pakistan.

In 2022, a La Niña event combined with a confluence of other factors to extend and intensify the monsoon over Pakistan, resulting in severe flooding. Unusually hot weather in spring and through the summer in Pakistan enhanced an intense depression from the Arabian Sea, bringing heavy rainfall to the southern regions (Mallapaty 2022). In the months of March and April 2022, an atypical time of year to witness severe heat, temperatures rose to more than 50 °C in some parts of the country, incurring various damages including wheat yield and livestock losses, forest fires, damage to infrastructure, and health issues. The hot summer also amplified the melting of Pakistan's 7000 glaciers that feed the Indus river (NASA Earth Observatory 2022), though the relative contribution of glacial meltwater to the flooding is unknown (Mallapaty 2022) and likely much smaller than the rainfall itself. The scale of destruction from this flooding is already expected to be far higher than 2010, which was the biggest flooding event faced by the country.

In 2010, the flooding was triggered by a trough in the upper atmosphere associated with the mid-latitude jet-stream[21]. The presence of a mid-latitude westerly trough aloft in the north and low-level moisture feeding through monsoon flow along the Himalayas and also the direct south-westerly current from the Arabian Sea resulted in the heavy downpour in the northern part of the country from 28 to 30 July. This event resulted in the catastrophic riverine flooding that started from the northern part of the Indus basin. Since the Indus basin traverses Pakistan from north to south and nearly bisects the physical territory of the country longitudinally, the 2010 floods impacted a large portion of the country, particularly the regions along the riverbanks.

Unlike 2010, which saw more than 300% of climatological rainfall over a period of three weeks in July (di Capua *et al* 2021), the 2022 monsoon season received multiple depressions (one of the flood-producing mechanisms during the monsoon season in Pakistan see S1 for details) from the Bay of Bengal in the months of July and August, which particularly impacted the two southern provinces of Sindh and Balochistan. Figure 1 shows eight tracks of monsoon depression observed during the 2022 season, sourced from the Pakistan Meteorological Department (PMD). Whereas monsoon depressions generally travel towards the northern part of the country during the monsoon season, all eight tracks were directed towards the southern provinces of Sindh and Balochistan this year, resulting in more than 500% of climatological rainfall during the two months of July and August, relative to their long-term average.

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[21] https://earthobservatory.nasa.gov/features/PakistanFloods

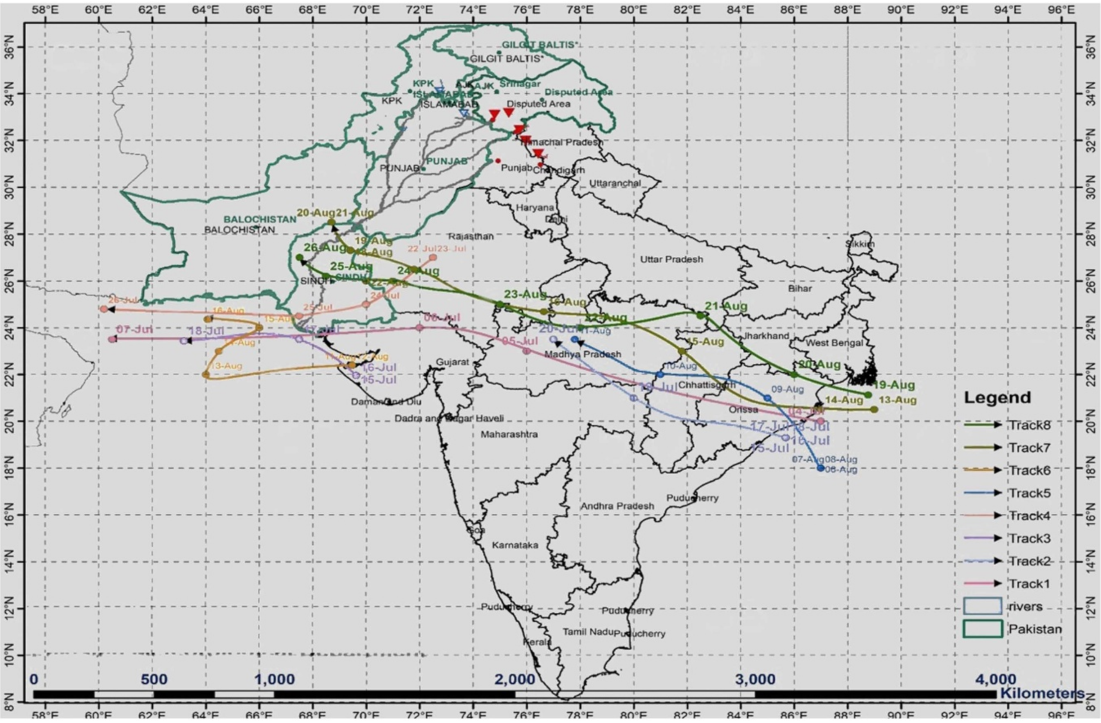


Figure 1. Movement of monsoon depressions from Bay of Bengal across India and Pakistan during the monsoon season 2022. Track 1 (4–7 July), Track 2 (16–20 July), Track 3 (15–18 July), Track 4 (22–26 July), Track 5 (6–11 August), Track 6, (11–16 August), Track 7 (13–21 August), and Track 8 (19–26 August) are eight tracks of monsoon depression during July–August 2022. The triangles indicate dams in India (red) and Pakistan (blue). (Source: Pakistan Meteorological Department).

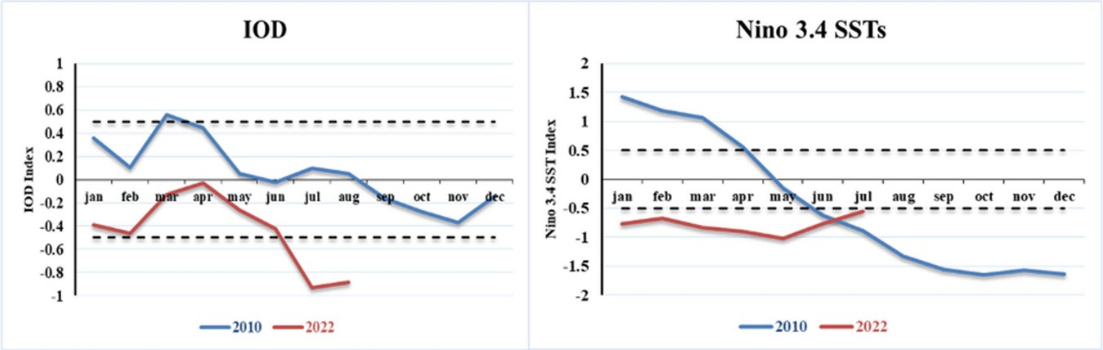


Figure 2. Comparison of La Niña (Nino 3.4 index) and IOD between 2010 and 2022 flooding events.

2.1.1. Role of La Niña

A commonality between the 2010 and 2022 events is the occurrence of La Niña in the tropical central Pacific. Figure 2 (*right*) shows that the La Niña pattern was more intense in 2010 compared to 2022. However, unlike 2010, a negative Indian Ocean Dipole (IOD) exists in 2022, as shown in figure 2 (*left*). The concurrence of La Niña and negative IOD during 2022 indicates anomalous warmer sea surface conditions in the eastern Indian ocean (around Indonesia), thus providing additional moisture to feed monsoon depressions. Figure 4 shows the correlation between July and August precipitation in the CPC dataset averaged over the Indus basin and the NCDCv5 ERSST SST values (Huang *et al* 2017). The strong correlation over the NINO 3.4 region suggests that the strong La Niña has indeed enhanced the precipitation over the Indus basin.

2.1.2. Role of heat low over Pakistan

Heat lows during the month of May over Pakistan are found to be associated with excessive precipitation in the following monsoon season (Bansod and Singh 1995). Figure 3 shows the anomalies in mean sea level pressure and the 2 m-temperature in the month of May, for the years 2010 (figure 4 (*left*)) and 2022 (figure 4 (*right*)) over a larger region covering India and Pakistan. The anomalies for 2022 May (figure 4 (*right*))

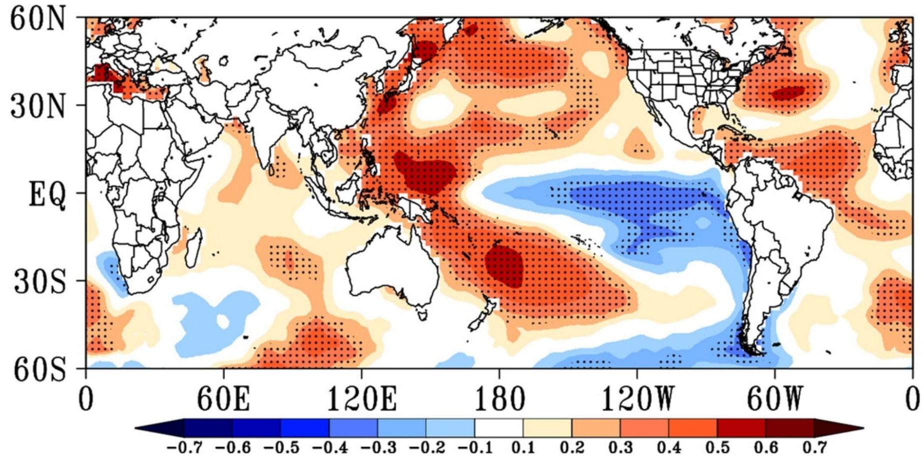
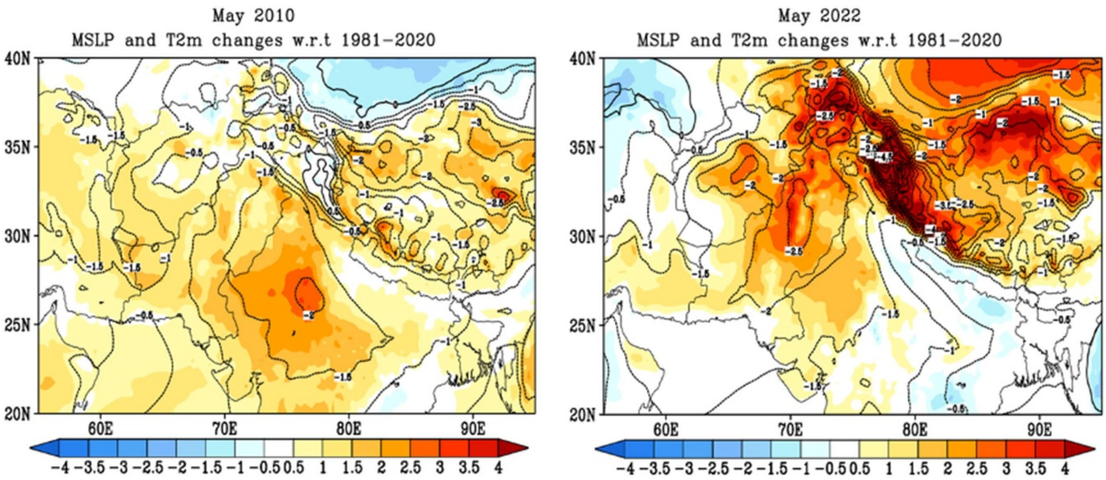


Figure 3. Correlation between rainfall (CPC dataset) over July–August in the Indus basin and global ERSST sea surface temperatures for months July–August, calculated over years 1979–2022. Dotted areas show the significance at 90% level by using student *t*-test.


May 2010
MSLP and T2m changes w.r.t 1981–2020

May 2022
MSLP and T2m changes w.r.t 1981–2020

Figure 4. 2 m temperature (shaded) and mean sea level pressure (isobars) anomalies from ERA5.

suggests that the high surface temperatures may have led to the intensification of the heat low over Pakistan, which in turn may have influenced the migration of monsoon depressions toward the southern provinces-Balochistan and Sindh.

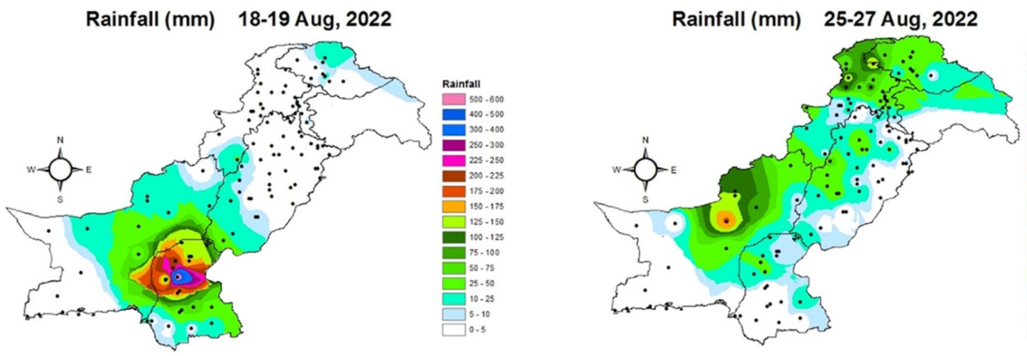
It is worth mentioning here that a study carried out by World Weather Attribution (2022) earlier this year concluded that climate change made that particular heat wave 30 times more likely as compared to the pre-industrial world.

2.1.3. Role of mid-latitude jet stream

It is well established that in 2010, a blocking event in the jetstream occurred, which caused a simultaneous occurrence of a heatwave in Russia (Met Office n.d.) and flooding in Pakistan.

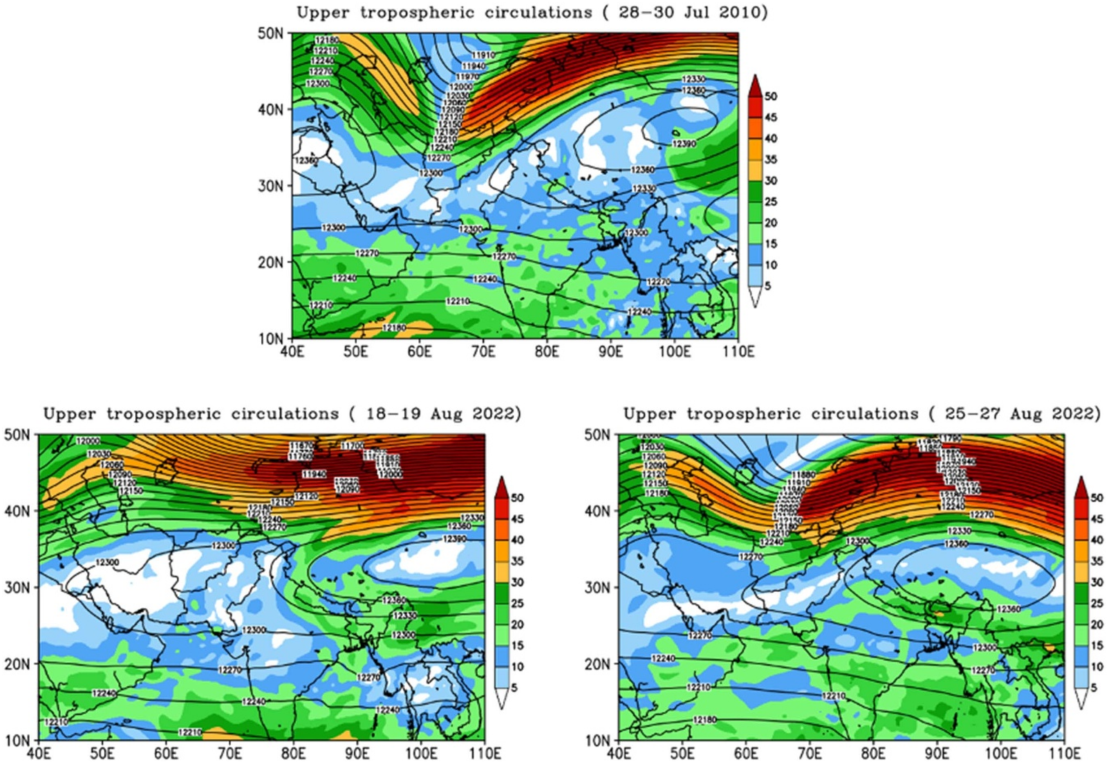
In 2022, in addition to the monsoon depression received by the southern provinces of Sindh and Balochistan, the northern province of Khyber Pakhtunkhwa (KP) and north western Balochistan received heavy rainfall towards the end of August (shown by red circles in the right-hand panel of figure 5) which was not connected with the monsoon disturbances discussed earlier and was speculated to be associated with the mid-latitude jet stream. This particular downpour in KP resulted in the Indus riverine flooding which continued until September in the downstream Indus river.

To explore the difference in the patterns of rainfall events further, we looked at two separate events in August 2022. An event from 18th to 19th August which caused heavy rainfall in Sindh, and another spell resulting in high level of rainfall in KP and western Balochistan from 25th to 27th August as shown by the red circles in figure 6. While it is evident that the 18th–19th event over Sindh occurred because of monsoon


Rainfall (mm) 18-19 Aug, 2022

Rainfall (mm) 25-27 Aug, 2022

Figure 5. Rainfall for the two events in august 2022 (source Pakistan Meteorological Department Data).


Upper tropospheric circulations (28–30 Jul 2010)

Upper tropospheric circulations (18–19 Aug 2022)

Upper tropospheric circulations (25–27 Aug 2022)

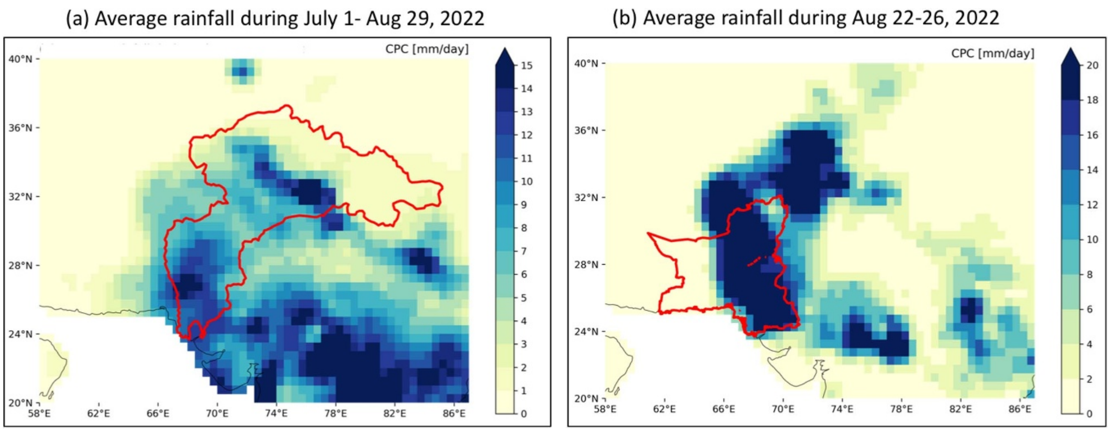
Figure 6. 200 hPa geopotential heights (isobars) and wind speed (unit; meter/second, shaded) from ERA5 data.

depressions, the other event over KP and western Balochistan cannot be explained by the tracks in figure 1. We compared the atmospheric patterns leading to the two events along with its comparison with the 28–30 July 2010 event.

Figure 6 shows the upper tropospheric circulation for the three events at 200 hPa. The 2010 event corresponds very well with the 25–27 August 2022 event, with both having a prominent trough over Afghanistan and the trough exit region lying over Pakistan including KP and north-western Balochistan. However, the trough-like pattern associated with the jet stream is simply missing for the 18–19 August event. This implies that similar to the 2010 event, 25–27 August 2022 rainfall event can be attributed to the trough associated with the mid-latitude jet stream.

2.2. Event definition

Taking this analysis into account and considering that the atmospheric conditions leading to rainfall in the southern provinces is different from the northern part of the country, we conduct a probabilistic event attribution analyse of the 2022 event over two regions: (i) the whole Indus basin as shown by the red highlight in figure 7(a) and (ii) a region combining the southern provinces of Sindh and Balochistan (figure 7(b)). We also use two different temporal scales to distinguish the long-duration the monsoon season


(a) Average rainfall during July 1- Aug 29, 2022

(b) Average rainfall during Aug 22-26, 2022

Figure 7. (a) Observed average 60-day rainfall for 1 July–29 August 2022. The red highlight shows the Indus river basin (b) 5-day rainfall for 22–26 August, 2022. The study region encompassing Balochistan and Sindh is highlighted in red.

and the acute episodes above mentioned. This distinction is further motivated by differences in the corresponding physical and dynamical mechanisms.

Concrete the two event definitions for the remainder of this study are: (1) annual maximum of the mean 60 day precipitation during June–September, over the Indus river basin (figure 7(a)) (capturing the monsoon rainfall season), and (2) the annual maximum of the mean 5 day precipitation in June–September over the Sindh and Balochistan provinces together (figure 7(b)) (the most extreme spell). These two metrics align most closely with the impacts of the event, capturing both the short heavy precipitation in the southern provinces, as well as the longer spell over Pakistan.

3. Probabilistic event attribution

In this analysis we analyse time series from the Indus basin (figure 7(a)) and the combined provinces of Sindh and Balochistan (figure 7(b)) of daily precipitation values where long records of observed data are available. Methods for observational and model analysis and for model evaluation and synthesis are used following (Philip *et al* 2020) with supporting details found in (Ciavarella *et al* 2021, van Oldenborgh *et al* 2021, Li and Otto 2022).

The analysis steps include: (i) trend calculation from observations; (ii) model validation; (iii) multi-method multi-model attribution and (iv) synthesis of the attribution statement.

We calculate the return periods, probability ratio (PR; the factor-change in the event's probability) and change in intensity of the event under study in order to compare the climate of now and the climate of the past, defined respectively by the GMST values of now and of the preindustrial past (1850–1900, based on the Global Warming Index[22]). To statistically model the event under study, we use a generalised extreme value (GEV) distribution that scales with global mean surrface temperature (GMST) for both the 5 day and the 60 day event definitions. Next, results from observations and models that pass the evaluation tests are synthesised into a single attribution statement.

3.1. Analysis of gridded data

Figure 8 shows the annual precipitation time-series for CPC (1979–present; *left)*, ERA5 (1950–present; *middle*) and IMERG (2000–present; *right*) for the Indus river basin (figure 8(a)) and the smaller region of Balochistan and Sindh (figure 8(b)). Overall, these records are in agreement, however, due to the shorter length of the CPC and IMERG datasets and inconsistencies in the magnitude of the 2022 event among the three datasets, it is difficult to select one of these as the primary data. We thus use all three datasets (figure 8) for computing observed return periods of the events and synthesis, and CPC and ERA5 for model evaluation. More details on these datasets can be found in the supplementary material section S2.1.

The left panels in figure 9 show the response of June to September (JJAS) maximum of 60 day average precipitation to the global mean temperature, for the Indus river basin, based on the gridded CPC, ERA5 and IMERG datasets. The right panels in figure 9 show the return period curves in the present, 2022 climate and the past climate when the global mean temperature was 1.2 °C cooler. We find that the return period of the

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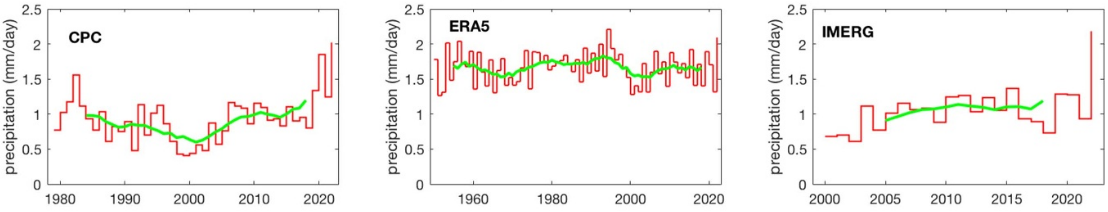
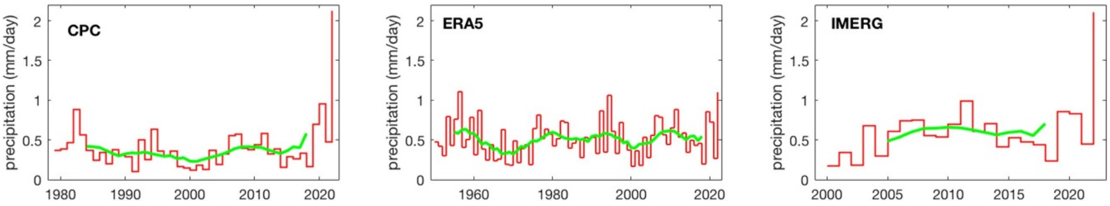
[22] www.globalwarmingindex.org



(a) Indus Basin



(b) Balochistan- Sindh

Figure 8. Time series of annual average rainfall (mm/day) along with the ten-year running mean (shown by green line) for (a) the Indus river basin and (b) the southern provinces of Balochistan and Sindh (bottom), based on CPC (left), ERA5 (middle) and IMERG (right) rainfall datasets.

maximum 60 day rainfall over the Indus Basin in JJAS 2022 in the 2022 climate is consistent across all datasets, ranging from 85 to 96 years. We round this to 100 years for the remainder of the analysis.

Similar plots for the JJAS maximum 5 day average rainfall in the southern provinces of Balochiostan and Sindh are shown in figure 10. The return periods of this event in the current, 2022 climate are also found to closely match in all of the datasets (right panels in figure 10), again the return period is rounded to 100 years for the rest of the analysis.

3.2. Model analysis

We conduct the same analyses that have been done for the observations with a suite of climate models, following the multi-model approach. We consider the CORDEX South Asia ensemble with in total, 24 simulations with 2 resolutions: 0.44° (about 50 km) (16 models) and 0.22° (about 25 km) (8 models), described in SI section S1.2.

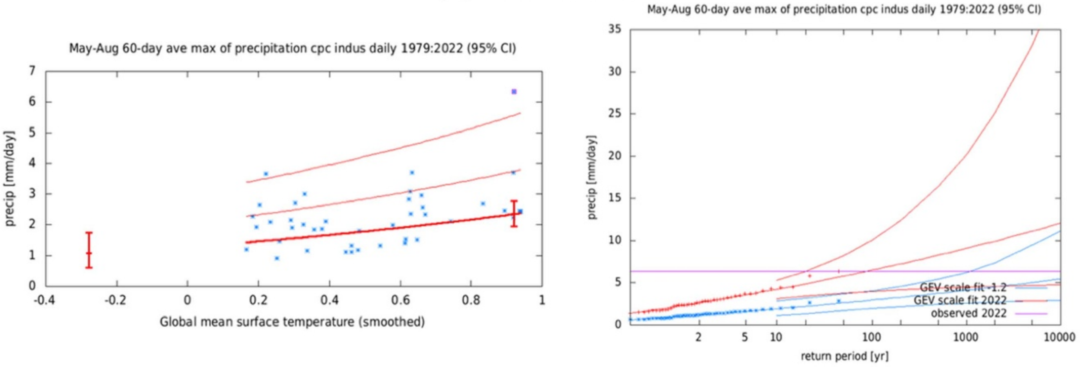
The second ensemble considered in this study is GFDL-CM2.5/FLOR. This is a fully coupled climate model developed at the Geophysical Fluid Dynamics Laboratory (GFDL, Vecchi *et al* 2014) with horizontal resolution of 50 km for land and atmosphere and 1 degree for ocean and ice. The ten ensemble simulations cover the period from 1860 to 2100, and include both the historical and RCP4.5 experiments driven by transient radiative forcing from CMIP5 (Taylor *et al* 2012).

We also use the HighResMIP SST-forced model ensemble (Haarsma *et al* 2016), the simulations for which span from 1950 to 2050. The SST and sea ice forcings for the period 1950–2014 are obtained from the $0.25° \times 0.25°$ Hadley Centre Global Sea Ice and SST dataset that are area-weighted regridded to match the climate model resolution. For the 'future' time period (2015–2050), SST/sea-ice data are derived from RCP8.5 (CMIP5) data, and combined with greenhouse gas forcings from SSP5-8.5 (CMIP6) simulations (see section 3.3 of (Haarsma *et al* 2016) for further details).

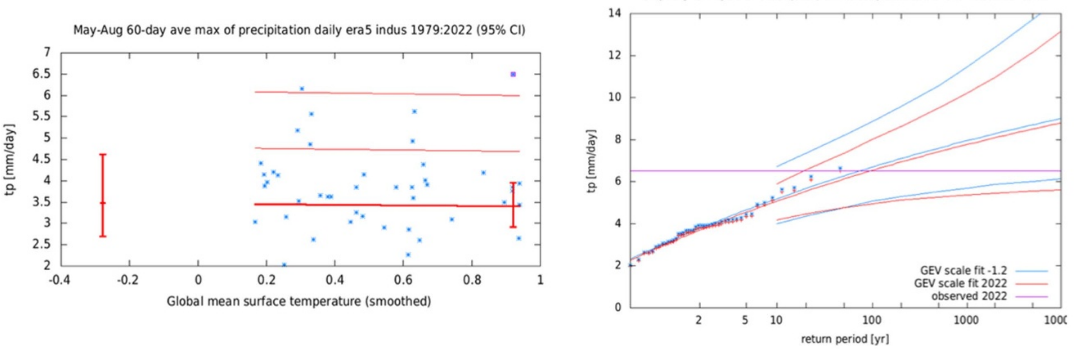
We evaluate these models based on the following criteria:

- Satisfactory seasonal cycles for the index used (here, rainfall averaged over the Indus basin and over the Southern regions), with an emphasis on capturing the monsoon peak in the right months (from July to September);
- Satisfactory spatial patterns of mean rainfall during the central monsoon months (July and August), capturing the West–East gradient of mean rainfall over Pakistan;
- Model fit parameter (dispersion and shape) confidence intervals that overlap with those from observations. If the best estimate of the observations is within the models' confidence interval we label the model as 'good' for this test, if confidence intervals overlap it is deemed 'reasonable'. For the observations we pooled the two confidence intervals of ERA5 and CPC, by taking the lowest and highest values of the two 95% confidence intervals to represent the observational uncertainty range;
- In addition, we checked the bias of the magnitude corresponding to a 100 year return value for models. For the case of the 5 day event definition, rainfall totals corresponding to a 100 year return value exhibited large positive biases in some models (e.g. more than twice the observed value), in which case they were discarded.

(a) Based on CPC



(b) Based on ERA5



(c) Based on IMERG

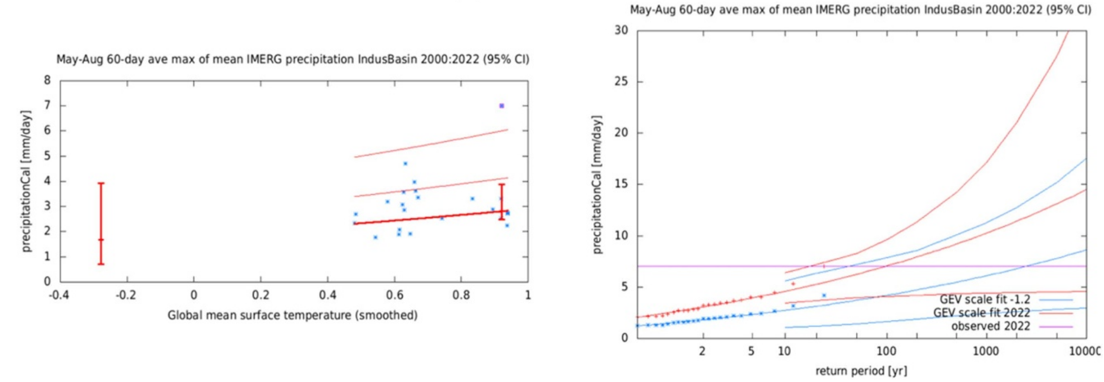


Figure 9. GEV fit with constant dispersion parameters, and location parameter scaling proportional to GMST of the index series, for the Indus river basin based on three gridded datasets- (a) CPC (b) ERA5 and (c) IMERG. The 2022 event is included in the fit. Left: observed max. 60-day average rainfall in the JJAS season as a function of the smoothed GMST. The thick red line denotes the time-varying location parameter. The vertical red lines show the 95% confidence interval for the location parameter, for the current, 2022 climate and a 1.2 °C cooler climate. The 2022 observation is highlighted with the magenta box. Right: return time plots for the climate of 2022 (red) and a climate with GMST 1.2 °C cooler (blue). The past observations are shown twice: once shifted up to the current climate and once shifted down to the climate of the late nineteenth century. The markers show the data and the lines show the fits and uncertainty from the bootstrap. The magenta line shows the magnitude of the 2022 event analysed here.

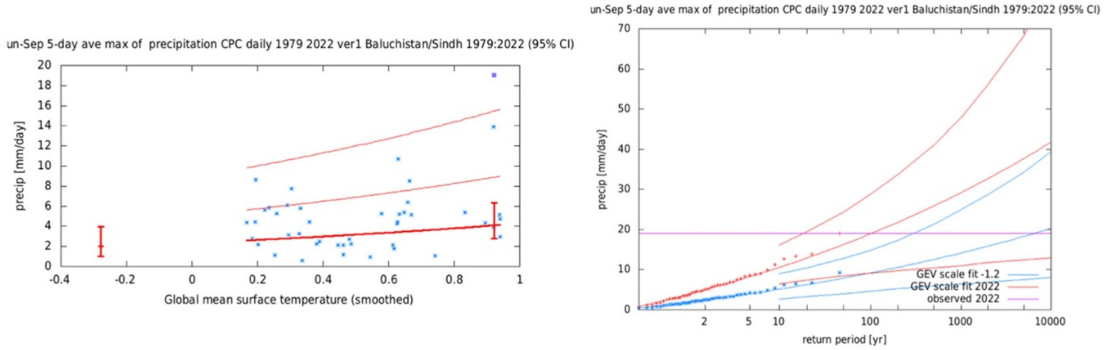
Supplementary section S3 provides the results of this assessment. Only models labelled as 'good' or 'reasonable' are selected for the analysis. For the Indus basin 21 models pass this test, but only 11 for the smaller region.

In a next step we conduct the same analysis as done in section 3.1 for each individual model. A tabled overview of these results can be found in the supplementary material S3. Figures 11 and 12 below provide a graphical representation of the PRs for each model (figures 11 / 12 right-hand side, red bars) and intensity changes (figures 12 / 13 left-hand side, red bars). We further repeat the analysis comparing a climate of 2 °C of global warming with todays 1.2 °C-world (figures 13 and 14, red bars).

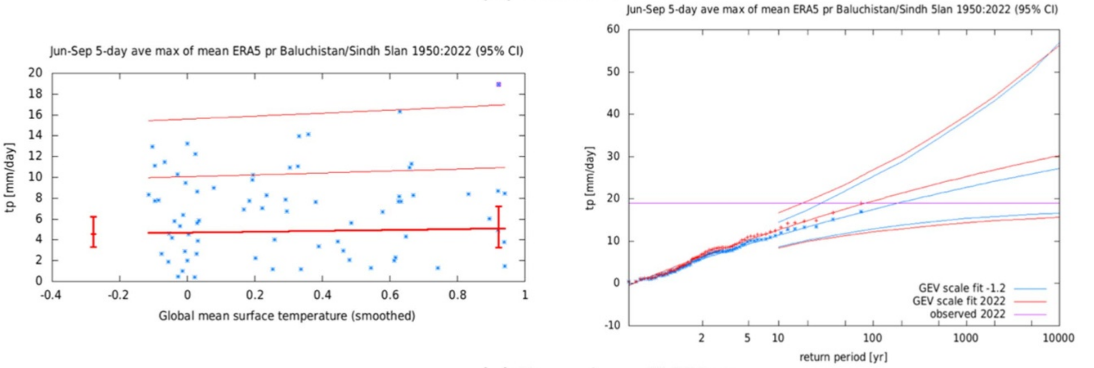
3.3. Hazard synthesis

To estimate an overarching result of the probabilistic analysis we calculate the PR as well as the change in intensity using observations (in this case reanalysis data ERA5, and the two observational products CPC &

(a) Based on CPC



(b) Based on ERA5



(c) Based on IMERG

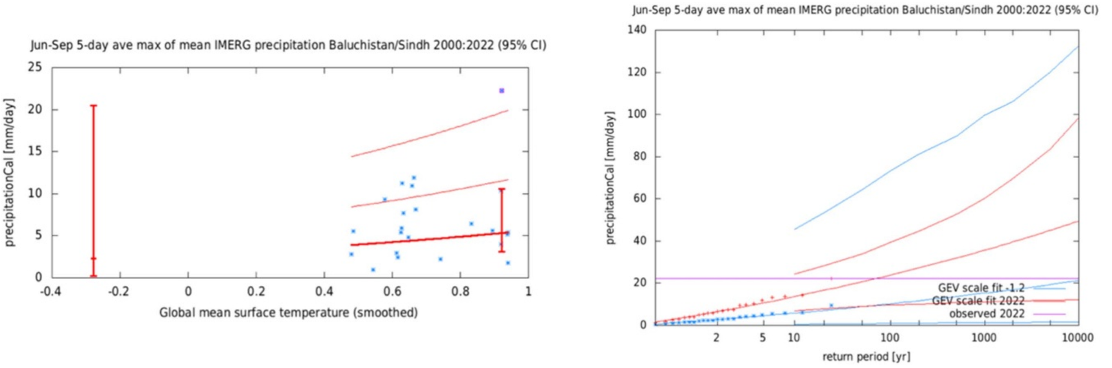


Figure 10. Same as figure 9 for the region encompassing the southern provinces of Balochistan and Sindh based on (a) CPC (b) ERA5 and (c) IMERG datasets.

IMERG) and models for the two event definitions first separately as described above then statistically combined. Models which do not pass the validation tests described above are excluded from this synthesis analysis. The aim is to synthesise results from models that pass the evaluation along with the observations, to give an overarching attribution statement. Observations and models are combined into a single result in two ways if they seem to be compatible. Firstly, we neglect common model uncertainties beyond the model spread that is depicted by the model average and compute the weighted average of models and observations: this is indicated by the magenta bar in figures 11 and 12. As, due to common model uncertainties, model uncertainty can be larger than the model spread, secondly, we also show the more conservative estimate of an unweighted average of observations and models, indicated by the white box around the magenta bar in the synthesis figures.

For both event definitions only few models pass the evaluation. The remaining models as well as the three observational products show very differing results and very large uncertainties. Due to these large uncertainties as well as the lack of structural diversity in the remaining models we refrain from quantifying the role of anthropogenic climate change in an overarching result. In other words, we do not believe that the synthesis provides a robust estimate of the role of anthropogenic climate change.

Instead we use the observations and models separately to inform our overarching conclusion in section 5.

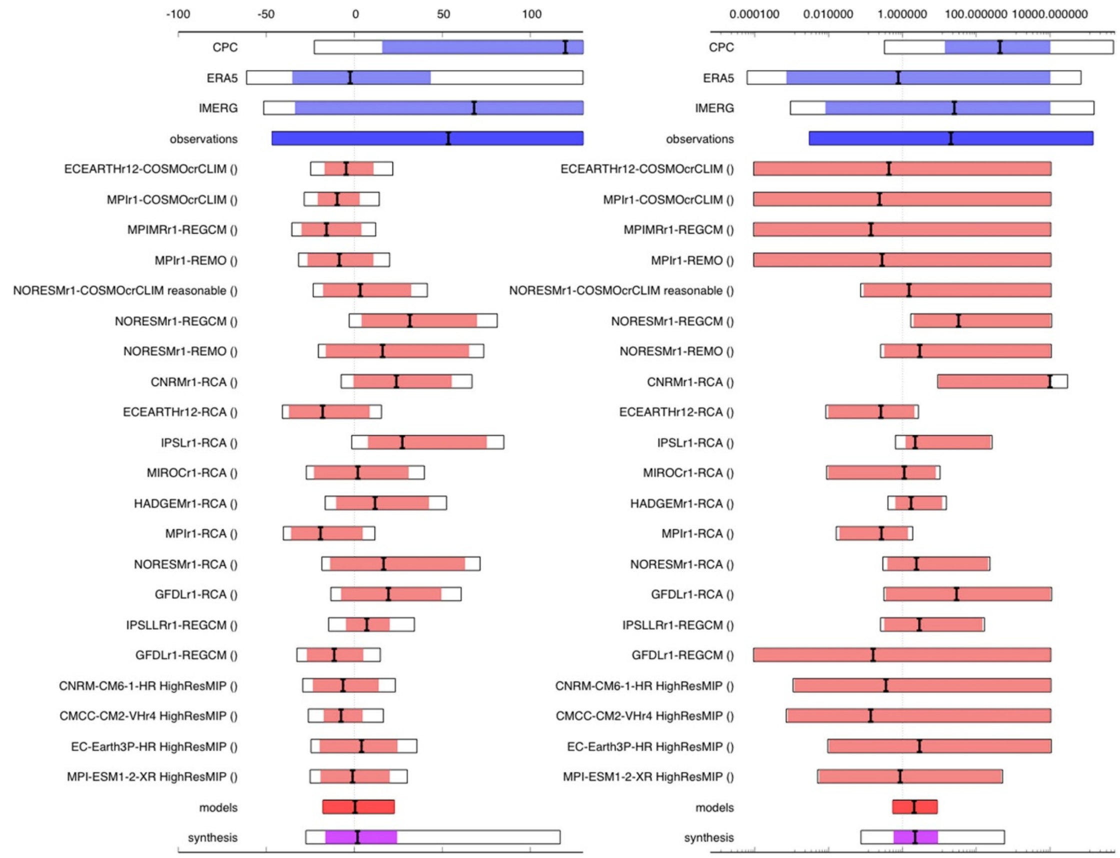


Figure 11. Synthesis of intensity change (left) and probability ratios (right), when comparing the 100-year 60-day heavy rainfall event over the Indus river basin with a 1.2 °C cooler climate.

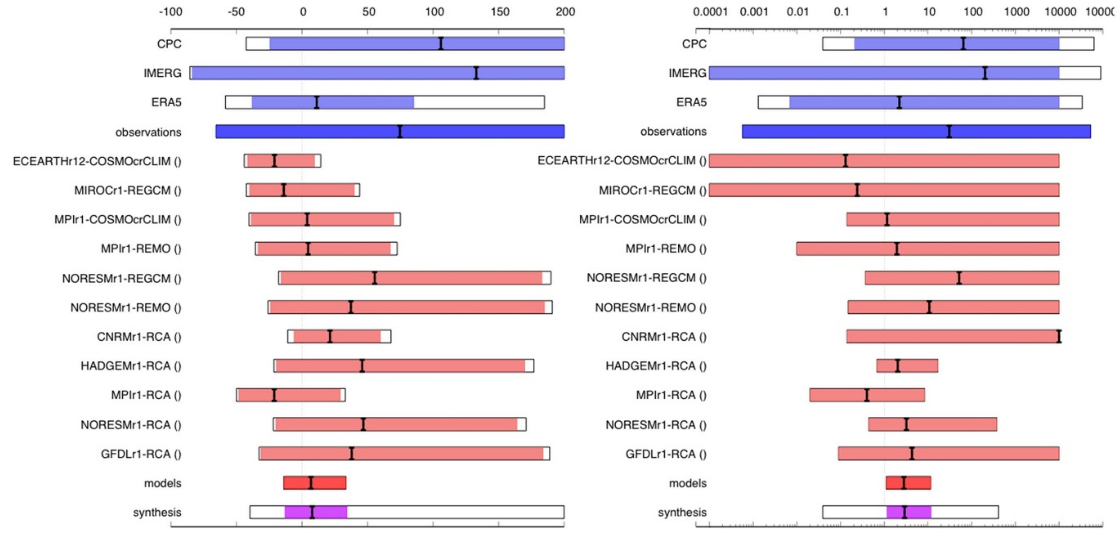


Figure 12. Synthesis of intensity change (left) and probability ratios (right), when comparing the 100-year 5-day heavy rainfall event over the region encompassing Balochistan and Sindh, with a 1.2 °C cooler climate.

For the 60 day and the 5 day extreme rainfall, the majority of models do show an increase in likelihood (right panels in figures 11 and 12) and intensity (left panels in figures 11 and 12) that is potentially very large, with best estimates of a change in intensity of up to 30% for the large region (figure 13(*left*)) and up to 50% for the small region (figure 14(*left*)), respectively.

Projecting the changes in likelihood and intensity for a 0.8 °C warmer future, figures 13 and 14 again show large discrepancies between the models. Despite this, models project a statistically significant change for the short-duration event with intensities increasing by 13% (figure 14 (*left*)) and probabilities increasing

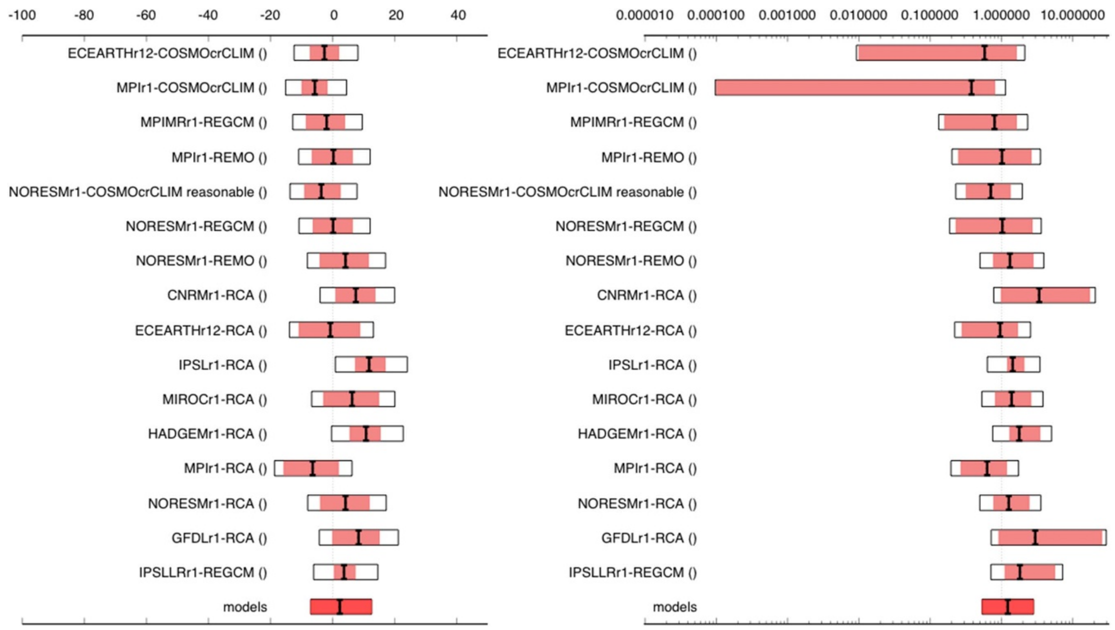


Figure 13. Synthesis of intensity change (left) and probability ratios (right), when comparing the 100-year 60-day heavy rainfall event over the Indus river basin with a with a 0.8 °C warmer climate (2 °C since pre-industrial).

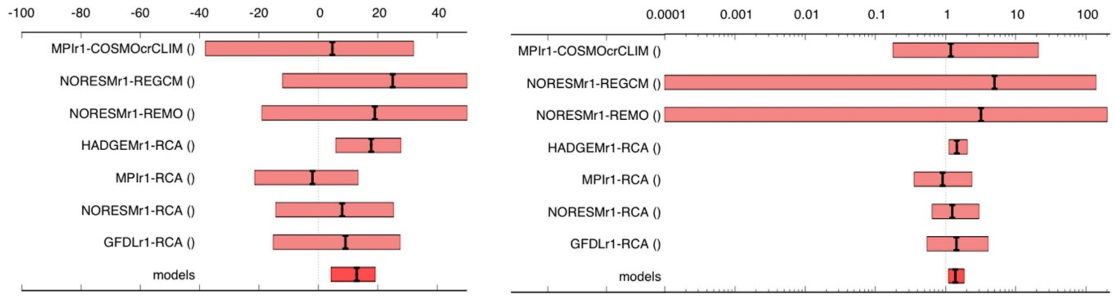


Figure 14. Synthesis of intensity change (left) and probability ratios (right), when comparing the 100-year 5-day heavy rainfall event over the region encompassing Balochistan and Sindh, with a 0.8 °C warmer climate (2 °C since pre-industrial).

by 40% (figure 14 (*right*)). This increase is compatible with but slightly larger than what we expect from the Clausius–Clapeyron relationship. We note that these projected changes are on average smaller than those in the published literature for the region (e.g. Gutiérrez *et al* 2021). This adds more confidence to the models projecting a high increase. Given however that the literature in general encompasses a larger region with less natural variability this is not surprising, but renders reliable quantitative projections difficult.

4. Vulnerability and exposure

While rainfall in 2022 was exceptionally high, heavy rains and extensive flooding were also experienced in Pakistan in the recent past, for example 2010, 2011 and 2012 (Rasmussen *et al* 2015). Pakistan receives most of its rainfall during the monsoon season and thus flooding patterns in Pakistan are predictable (Webster *et al* 2011), downstream areas of the Indus River are normally the worst affected and small towns and villages away from urban centres are inundated with water, especially in the province of Sindh (Syvitski and Brakenridge 2013, Busby *et al* 2018, Ali *et al* 2020a). Despite this knowledge, addressing the structural causes of vulnerability and exposure, especially in downstream Pakistan, remains a significant challenge.

4.1. Water management along the Indus Delta

Studies subsequent to the devastating 2010 floods (for example, the Report of the Flood Inquiry commissioned by the Supreme Court, see Khan 2011, Mustafa and Wrathall 2011) have concluded that it was not just the result of exceptional weather events but rather 'that most damage was caused by dam and barrage-related backwater effects, reduced water and sediment conveyance capacity, and multiple failures of irrigation system levees'(Syvitski and Brakenridge 2013). Further, this research suggests that reinforcing existing engineering structures would not prevent future flooding and warned that such a flooding disaster was certain to take place during future rains (Syvitski and Brakenridge 2013). These findings illustrate two wider and significant causes of vulnerability and exposure in towns and villages along the Indus Delta. First, a river development paradigm pursued by state planners based on engineering-driven interventions to harness water as a 'resource' with little regard for local environments (Akhter 2015, Aijaz and Akhter 2020, 2022). Secondly, reliance on an irrigation management system first constructed by the British Raj to meet other political and state-building ends rather than providing a channel for equitable water distribution (Daniel Gilmartin 1994, Mustafa 2007, Haines 2013).

The areas affected by the floods were preliminary rural (64% of the population lives in rural areas) farmlands. Agriculture is an important part of Pakistan's economy, accounting for 26% of GDP (Rehman *et al* 2015). The Indus river provides water for nearly 90% of food production in Pakistan, and 39% of the country's labour force is engaged in agriculture with wheat, rice, cotton and sugar cane being the primary crops[23]. It is the people who depend on agriculture who have been most vulnerable in the face of these floods. This reveals some of the issues with the way water is channelled and diverted, contributing to exposure and vulnerability of communities living amidst these hydraulic systems.

State policy in Pakistan has been to rely on a river engineering paradigm and hydrological mega projects for flood management. This has tended to create a number of drainage problems followed by problems related to sedimentation with the infrastructure aging (Mustafa and Wrathall 2011). The lower Indus Basin, for example, has been known to be vulnerable to drainage 'failures', even during non-flood years (Basharat and Rizvi 2016), leaving it particularly exposed in the face of high-intensity rainfall. At one level, while large-scale and highly engineered drainage projects have been constructed (such as the right bank outfall drain and the left bank outfall drain [LBOD]) to drain irrigation water out into the sea, the problems associated with these projects are well documented (Ali Asghar Mahessar *et al* 2019). The back-up of drainage flows on the LBOD was responsible for flooding large parts of Badin District in Sindh in 2010 (Siddiqi 2019). More generally, long-term reduction in watercourse channel capacity in these hydraulic systems due to sedimentation was also considered a key reason exacerbating those floods (Mustafa and Wrathall 2011). Beyond engineering problems or failures, there is also wider conversation taking place on whether Pakistan's ideological bias towards modernist engineering solutions (Akhter *et al* 2022) needs to be re-considered in favour of a more decolonial approach (Mustafa 2022).

Since the early twentieth century, floods along the River Indus have been managed by breaching of levees and intentionally spilling flood water (Asif *et al* 2007, Mustafa and Wrathall 2011). Flood vulnerability is not only dependent on political power today, but also on historically contingent processes of social engineering—location of land in connection to water sources has been dependent on loyalty to Crown and state—undertaken by the colonial and post-colonial state (Mustafa *et al* 2019). Similarly, diverting excess water to the countryside to protect cities is a policy continuing since British colonial rule (Mustafa and Wrathall 2011).

As a consequence of the nation's recurring floods and ensuing farmland devastation, evidence suggests that the agricultural sector is experiencing a shift from cash crops to livestock production (Jamshed *et al* 2017). However, large farm animals are particularly vulnerable to drowning in floods and estimates on loss of livestock in Sindh are in the hundreds of thousands (Latif 2022).

4.2. Disaster management policy and early warning systems (EWSs)

The primary policy framework for disaster preparedness and response is laid out in the National Disaster Management Act passed by Parliament in 2010, in part as a response to the devastating floods during that year (Ahmed 2013). It follows a three-tier disaster management system that assigns roles and responsibilities for 'preparedness, response, recovery and rehabilitation and reconstruction' to national, provincial and district level disaster management authorities[24]. This institutional architecture does not provide a roadmap for instituting disaster risk management at a local or community level. In an era of community based disaster risk management and participatory disaster risk assessments, Pakistan's disaster risk paradigm is centralised with limited avenues for hazard or vulnerability mapping to take place at local levels (as in countries such as Bangladesh or in The Philippines, see (Fernandez *et al* 2012, Habiba *et al* 2013). The resulting gulf between 'policies at the top' and 'voices at the bottom' has been documented in research (Mysorewalla 2019).

Following the Act, Pakistan launched its 10 year national disaster management plan in 2012, envisaging improvements including developing a multi-hazard EWS to cover riverine, flash, and glacial lake outburst

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[23] www.fao.org/pakistan/our-office/pakistan-at-a-glance/en/#:~:text=In%20total%2C%20the%20agriculture%20sector,densely%20populated%20forests%20and%20rangelands.

[24] https://cms.ndma.gov.pk/storage/app/public/pages/September2020/NDMA-Act.pdf.

floods. (NDMA 2012, Mukhtar 2018). In 2016 the World Bank launched a $120 million project in Sindh province to improve institutional capacity for disaster and climate risk management, increase the number of people receiving timely and more accurate early warning notifications, and establish a Sindh emergency service, among other activities intended to strengthen resilience to floods and droughts (World Bank 2021). The project is slated to end in 2024, and has made progress including preparing integrated disaster management plans for Sindh province, and upgrading and strengthening an emergency operations centre in the disaster management association, but as of 2021 there was no dedicated capacity to respond to emergencies by the Sindh emergency service (World Bank 2021). Reviews in the ensuing months will determine whether these investments were able to reduce impacts during the floods in 2022.

Analyses of Pakistan's broader framework for managing disasters often suggest that it is more reactive and while an EWS exists its delivery systems are unclear (Cheema *et al* 2016, Ali and Iqbal 2021), though local police stations and mosques have been used in the past (Mustafa *et al* 2015). However, since 2021 there have been some improvements, notably with the World Bank Sindh Resilience project reporting seven million people now receive timely and more accurate early warning notifications (World Bank 2021). It is also important to note that the 'flash' nature of much of the flooding, and large amount of water may also have significantly limited the effectiveness of any early warnings even if the systems were in place.

4.3. Infrastructure

The heavy rainfall and ensuing floods damaged over 1.7 million homes, 6.700 kilometres of road, 269 bridges and 1.460 health facilities (NDMA 2022, OCHA 2022a, Save the Children 2022). Early estimates of this devastation suggest that it totals US$30 billion (Business Standard 2022). Development in flood-prone areas is a factor that contributed to the high infrastructure damages during the current floods and policies that mandate flood zones that restrict building can be implemented to reduce this risk in the future (Mallapaty 2022). Many of the homes damaged in the current floods were traditional (mud) structures, and upgrading to flood resistant ones (concrete) through support for rebuilding efforts and awareness raising could increase resilience to future floods (Shah *et al* 2018).

According to initial assessments by the Pakistan Red Crescent Society (PRCS), the construction of a flood mitigation wall to limit flood damage to districts in KP such as Nowshera, Peshawar and Charsadda from floods, had positive effects during the 2022 floods. The PRCS found that despite the fact that the intensity of the current flooding was as high as the 2010 floods in this area, the damages would have been greater if the flood mitigation wall was not constructed. Similarly, the preparedness of disaster management authorities has also improved in some cases. Communities in Nowshera and Charsadda were evacuated 24–48 h before the floodwater inundated the area which has contributed to a lower mortality rate in these areas. While these are anecdotal instances of risk reduction, and a full assessment of the impact of these interventions is required, they do point to the potential for improved risk reduction and EWSs to reduce impacts on vulnerable people.

4.4. Household vulnerability

A review of household flood vulnerability following the 2010 floods in KP province revealed that key factors affecting household's flood vulnerability included respondents' socio-economic and demographic attributes (e.g. age, gender, education, income), their house-construction material, past experience with floods and social networks (Shah *et al* 2018). Other studies found similar results, including one that developed a multi-dimensional model for vulnerability based on empirical evidence and highlights social, economic, institutional, physical and attitudinal factors that contribute to vulnerability (Rana and Routray 2018). Using this framework, and a literature review of studies across Pakistan on flood vulnerability, we developed figure 15 highlighting the many factors that can increase risk during floods.

Vulnerability manifests through various impact pathways, for example, poverty can result in households living in poorly constructed (mud) houses, in areas where land is cheaper and more flood-prone, and far from health facilities. These factors can combine with socioeconomic factors (e.g. income, education, livelihood sources) in direct and in-direct ways, leading to greater risks from floods. Access to health facilities, type of latrine, access to information, distance from the nearest health facility, health facilities impacted by 2010 flood, and damaged water supply infrastructure were also highlighted as important factors affecting household vulnerability to floods (Rana and Routray 2018). Waterborne illnesses are already affecting people who have survived the direct effects of the current floods, illustrating the importance of access to water, sanitation and hygiene, and nearby health facilities (Sarkar 2022).

Women in Pakistan are more vulnerable to suffer the worst from the flood hazard because of their relative lack of mobility compared to men (Mustafa *et al* 2019). This largely stems from women's traditional role as primary caretaker for the elderly and children (Rana and Routray 2018, Shah *et al* 2018), but also the widespread ideal of purdah, gender segregation, which can incline women to stay at home rather than evacuating to a mixed-gender community shelter (Mustafa *et al* 2015). Even when women are able to reach

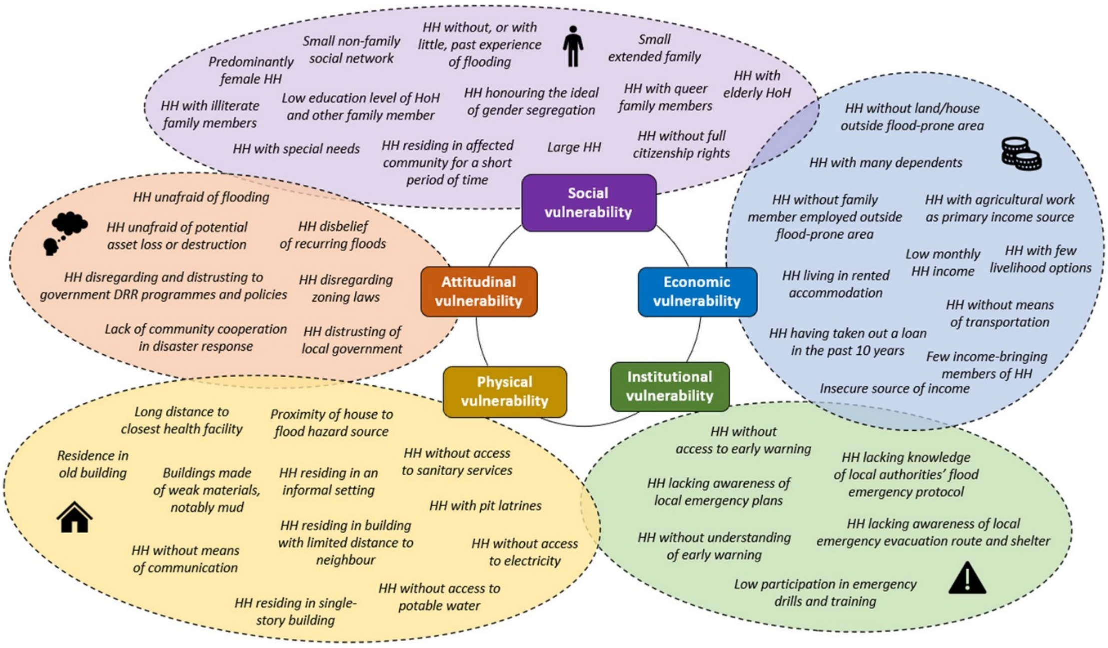

Figure 15. A visual representation of household (HH) factors contributing to vulnerability to floods in Pakistan categorised by types of vulnerability developed in (Rana and Routray 2018) based on empirical evidence and evidence from studies across Pakistan (Mustafa *et al* 2015, Sadia *et al* 2016, Shah *et al* 2018, Memon 2020, Ajani and van der Geest 2021, Anjum and Fraser 2021).

the safety of temporary shelters, such as flood settlement camps, they are vulnerable to physical violence (Memon 2020).

To address this gender issue, Pakistan's flagship social protection programme, the Benazir Income Support Programme makes cash transfers directly to women has had some success in addressing these forms of existing inequalities (Waqas and Awan 2018, Naseer *et al* 2021). The cash transfers after the floods in 2010 and 2011, were made to 'heads of households', typically men through ATM cards (Watan card and Pakistan card). Despite numerous positive outcomes (Siddiqi 2013, 2018), these programmes inadvertently marginalise households where the passing/absence of a usually male head is unrecorded, in turn, leaving women more vulnerable to non-payment of disaster relief. Severely marginalized, the country's transgender population is a notably vulnerable group (Mustafa *et al* 2015).

4.5. Environmental challenges facing the Indus Delta

The 2022 flooding has taken place within a broader context of the slow degradation of the Indus Delta downstream. The various river diversions and different large-scale projects mentioned earlier have changed natural ecological systems along the river with significant impacts on the wider delta. The reduction of freshwater discharge and changing patterns and levels of salinity in the water have all been evidenced in research (Khuhawar *et al* 2018, Wang *et al* 2019, Mahar and Zaigham 2021). These issues have produced various slow-onset disasters that include the changing environment of the delta, coastal erosion, intrusion of saline water, destruction of fertile land, shortage of drinking water, loss of mangrove vegetation, reduction in fish catch (Salman 2011, Laghari *et al* 2015). These regions and their communities are thus particularly vulnerable to any extreme weather event.

5. Conclusion

The flooding occurred as a direct consequence of the extreme monsoon rainfall throughout the summer 2022 season exacerbated by shorter spikes of very heavy rain particularly in August hitting the provinces Sindh and Balochistan which led us to consider two definitions of the event.

First, averaging just the trends in the observations (sections 2 and 3.3), we found that the 5 day maximum rainfall over the provinces Sindh and Balochistan is now about 75% more intense than it would have been had the climate not warmed by 1.2 °C, whereas the 60 day rain across the basin is now about 50% more intense, meaning rainfall this heavy is now more likely to happen. There are however large uncertainties in these estimates due to the high variability in rainfall in the region and relatively short observational datasets, and observed changes can have a variety of drivers, including, but not limited to, climate change.

Secondly, to determine the role of human-induced climate change in these observed changes we looked at the trends in climate models (section 3) with and without the human-induced increases in greenhouse gases. The regions involved are at the western extreme end of the monsoon region, with large differences in rainfall characteristics between dry western and wet eastern areas. Many of the available state-of-the-art climate models struggle to simulate these rainfall characteristics. Those that pass our evaluation test generally show a much smaller change in likelihood and intensity of extreme rainfall than the trend we found in the observations. This discrepancy suggests that long-term variability, or processes that our evaluation may not capture, can play an important role, rendering it infeasible to quantify the overall role of human-induced climate change as discussed in section 3.

However, the statistical methods are not the only information available, on the one hand we do know, for the 5 day rainfall event that the Clausius–Clayperon relationship will hold, and many studies discussed in section 3.3, even though they all contain major caveats point towards an increase in the likelihood and intensity of both events. This is corroborated by the fact that our future projections discussed in section 3 do also show an increase with further warming in particular for the short duration event. We therefore conclude, for the 5 day rainfall extreme, where most models and observations we have analysed show that intense rainfall has become heavier as the world has warmed, that climate change indeed increased the rainfall intensity up to 50% as the best estimate in some models. For the 60 day event we also cannot exclude, that climate change is indeed responsible for all of the observed increase in heavy rain, but the mechanisms are less well understood and projections are highly uncertain thus determining even the sign of the change remains impossible based on this assessment.

However, the hazard was only one component leading to the devastating floods. Both, current conditions and the potential further increase in extreme peaks in rainfall over Pakistan in light of human-caused climate change, suggest that there is an urgent need to reduce vulnerability to extreme weather in Pakistan.

In addition to the climatic hazard, the factors driving the devastating impacts for the 33 million people affected in Pakistan include the proximity of human settlements, infrastructure, and agricultural land to flood plains, limited ex-ante risk reduction capacity, an outdated river management system, underlying vulnerabilities driven by poverty, socioeconomic factors that disadvantage women, and ongoing political and economic instability. The extreme nature of the rainfall and subsequent floods means that some level of impact was likely unavoidable. The Pakistan government's established record in providing social protection interventions especially after disasters (World Bank 2013), and ongoing projects to strengthen resilience to floods, may have played a role in reducing the impacts of the current floods. However, there are still critical gaps in the full implementation and operationalisation of disaster management policies and plans developed following the 2010 floods. Rebuilding following the disaster also provides an opportunity to strengthen resilience and avoid future risk through stronger infrastructure designed for the new climate and considerations of flood risk when deciding where to rebuild.

Data availability statement

Almost all data are or will soon be available via the Climate Explorer.

For access to weather station data, please contact Pakistan Meteorological Department.

All data that support the findings of this study are included within the article (and any supplementary information files).

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