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# Climate Change Impacts on Monsoon Flood Situations in Pakistan †

**Hafsa Muzammil [1,2,*], Muhammad Zaman [1,*], Muhammad Adnan Shahid [1,2,*] Muhammad Safdar [1,2], Muhammad Danish Majeed [1,2,] Rehan Mehmood Sabir [1,2] and Sidra Azam [1]**

[1] Department of Irrigation & Drainage, University of Agriculture, Faisalabad 38000, Punjab, Pakistan; email1@email.com (X.X.); email2@email.com (X.Y.)
[2] Agricultural Remote Sensing Lab (ARSL), University of Agriculture, Faisalabad 38000, Punjab, Pakistan
* Correspondence: hafzamuzammal990@gmail.com (H.M.); muhammad.zaman@uaf.edu.pk (M.Z.); adnan.wmrc@gmail.com (M.A.S.)
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**Abstract:** In this study, we present a comprehensive and detailed analysis to identify and quantify spatial patterns of heavy, very heavy, and extremely heavy rainfall as well as their trends that have developed over the past seven decades (1951 to 2020) of the monsoon months (June to September) under a warming scenario. We also project these extreme rainfall counts during the near (2036–2060) and late 21st century (2075–2099) compared to the historical period (1990–2014). The 5-day maximum rainfall over the provinces of Sindh and Baluchistan is currently about 75% more intense than it would have been without climate warming by 1.2 °C and the 60-day rainfall across the basin is currently about 50% more intense. This means that heavy rainfall is now more likely to occur. Due to the high level of rainfall variability in the area, there is significant uncertainty in these estimations, and the causes of the observed changes are not just limited to climate change. However, most of the models and observations we have analyzed for the 5-day rainfall extreme indicate that severe rainfall has been heavier as Pakistan has warmed. According to some of these models, the intensity of the rainfall might have increased by 50% due to climate change under the 5-day event threshold. The model predicts that rainfall intensity will greatly rise in the future for the 5-day event in a climate that is 2ºC warmer than it was in preindustrial time, while the uncertainty is still quite high for the 60-day monsoon rainfall.

**Keywords:** climate change; floods; heavy monsoon; national disaster management authority; precipitation variations

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## 1. Introduction

The Indus Basin contains 1.10 million square kilometers, with Pakistan contributing 63 percent, India 29 percent, and Afghanistan and China 8 percent. These entire provinces such as the province of Khyber Pakhtunkhwa, Sindh, and towards the eastern part of Punjab and Baluchistan cover the Indus Basin River [1]. The Indus River arises in Tibet (China) at Mount Kailash (Mansarovar Lake) and is divided into two sections: Upper Indus and Lower Indus, the water flow from the upper side of the Indus and downstream of the Guddu barrage. Glaciers of Hindu Kush and Karakoram are supplied water to the Indus River, however, it is the main source of fresh water and it supports 90 percent of agriculture land, and industrial and household requirements.[2]

The Indu's basin hydrology is influenced by the interaction of three distinct regimes and their responses to climatic conditions: the glacial, nival (snow melt), and rainy regimes. To assess how climate change may affect the Indus Basin, an understanding of the hydrological processes that determine river flow is essential [3] About 25 to 35 percent of the water flow in the Indus River is generated by the glacial phase. Due to the region's naturally diversified geography and climate, its flow patterns are influenced by a wide range of responses. Summer temperature is positively connected with runoff rates in the glacial regime (i.e., higher temperature led to more runoff) and negatively correlated with summer precipitation [4].

Climate Change will have a significant impact on global socio-ecological systems in the future decades, affecting the hydrological cycle, agricultural production, and basic ecosystem [5]. Rising temperatures in basins that rely heavily on glacier melt will almost certainly result in a rise in stream flow in short term but a decrease in the long term. This is because the overall quantity of glacier melt is a tradeoff between increasing melt rates on the one hand and decreasing glacier volumes on the other. When the trend of glacier melt shifts from positive to negative [6], Due to climate change this warming effect is predicted to influence rainfall patterns and increase the frequency of extreme weather events such as flooding, drought, and other natural disasters. Furthermore, rising $CO_2$ concentrations will have a direct impact on crop growth and development, affecting agricultural land use and crop yields [7].

Planning for climate impacts, creating resistance to such impacts, and enhancing civilization's capabilities to react and recover are all aspects of adjustment [8]. This may help to decrease the damages and disruptions caused by climate change. Government should play a bigger role in promoting water demand reduction initiatives. Considering the risks of increasing per capita water shortages, provincial governments should take the initiative in increasing agricultural, industrial, municipal, and domestic water conservation [9]

This should include more investment for programs that encourage water conservation practices like flood and rainwater harvesting; as well as the use of high efficiency irrigation systems; improve irrigation canal maintenance; promote the breeding and cultivation of less water intensive; implement waste water recycling in urban areas; and install a more efficient thermal cooling system [10].Water pricing rules that properly reflect the true cost of water usage should also be implemented by governments [11].

## 2. Data and Methods

### 2.1. Observational Data

The National Climate Centre (NCC) of the Pakistan Meteorological Department PMD provided the daily gridded rainfall dataset with a spatial resolution of 0.25° × 0.25° during the monsoon (June- September) period between 1951 and 2020 over the Pakistan region. A network of 47 stations dispersed throughout the Pakistan landmass was used to create the gridded dataset.

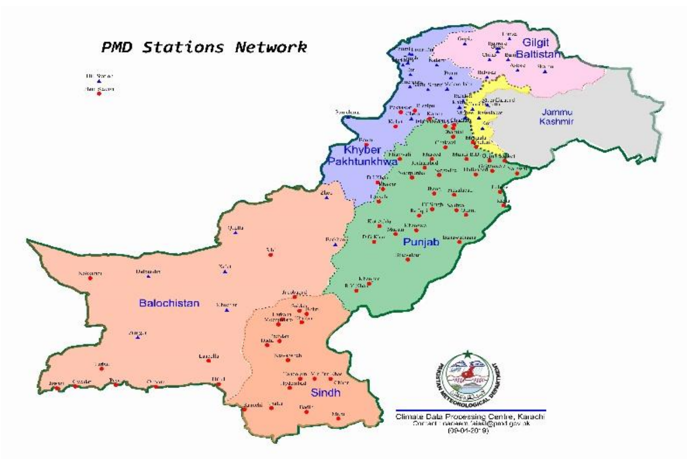


**Figure 1.** Pakistan Station point.

One of the main ways to understand how the climate has changed in the past and might change in the future is using climate models. In this analysis, we evaluate predicted changes in the frequency of extreme rainfall events for the near 21st century (2036–2060) and late 21st century (2075–2099) with a primary focus on the distribution of heavy, very heavy, and extremely heavy rainfall.

With the historical period typically beginning in 1950 (or 1970) and ending in 2005, followed by the Shared Socio-Economic Pathways scenarios until the 21st century, we used the model simulations that were available from the CMIP 6 (Couple Model Intercomparison Project Phase 6) over South Asia. Global Climate Model (GCM) simulations are downscaled and used to create regional climate model (RCM) simulations.

## 3. Result and Discussion

The research is a comprehensive understanding of how CIMP6 models reflect extreme events at the national and global levels. To understand changes in extreme occurrences the visualizations offer several viewpoints on past conditions as well as possibly the future. Future periods and scenarios with a focus on 2025, 2050, 2075, and 2085 can be compared to the baseline climate (Historical Period, 1985–2014, centered on 2000). The extreme indicators do not stand for location-specific (station level) extremes, but rather qualitative projection results that directly reflect global model output.

When compared to mean precipitation, extreme precipitation events often exhibit higher magnitudes of change and distinct indications. As the earth gets warmer, the ability of air to carry moisture increases exponentially, increasing the possibility of more precipitation. This can increase the risk of flooding since the more frequent occurrence of strong events is expected. Only in regions where precipitation is much less frequent can a trend toward more rainfall be reversed, resulting in an increase in return periods rather than a decrease in the frequency of major occurrences.

The characteristics of the climate as represented by extreme events and distinct from those of the long-term means since they reflect unusual weather events. Compare the maps to find any potential trends that are in contrast and different magnitudes of change between the largest event that occurred during the period and the mean precipitation as well as the extreme statistics indicators for various return periods for the globe and the country.

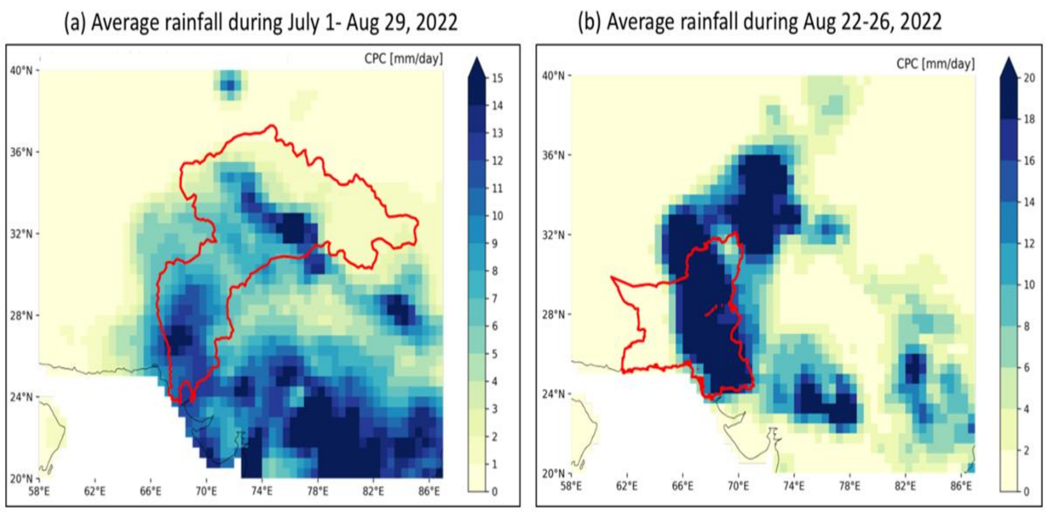


**Figure 2.** Annual maximum of the mean 60-day precipitation and the annual maximum of the mean 5-day precipitation in monsoon season at the site of Sindh and Baluchistan.

For a limited number of repetition intervals, return levels (precipitation amounts displayed in mm) are available. In addition, the relationship between the Return Periods

(Represented in years) and the spatial distribution of fixed precipitation magnitudes (also known as return levels) can be examined. When the Annual Exceedance Probability is needed, the inverse of the return period is required.

**Table 1.** Extreme Precipitation event from the year 1985–2014.

Largest 1-Day Precipitation for Pakistan

| Return Levels, Historical: 1985-2014 (center 2000) (mm) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 5-yr | | | 10-yr | | | 20-yr | | | 25-yr | | | 50-yr | | | 100-yr | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| Historical | 19.95 | 32.94 | 53.17 | 25.12 | 41.06 | 68.42 | 30.55 | 50.34 | 85.97 | 32.24 | 53.77 | 91.76 | 38.09 | 65.71 | 111.56 | 44.56 | 79.24 | 140.57 |

| Return Period, Historical: 1985-2014 (center 2000) (years) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 25mm | | | 50mm | | | 100mm | | | 150mm | | | 200mm | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| Historical | 0.97 | 3.16 | 11.90 | 4.27 | 28.62 | 377.27 | 92.60 | 852.68 | 6584.30 | 330.36 | 3160.90 | 10321.03 | 792.62 | 4680.28 | 11719.28 |

**Table 2.** Annual Exceedance Probability of precipitation.

| Annual Exceedance Probability, Historical: 1985-2014 (center 2000) (occurrence/year) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 25mm | | | 50mm | | | 100mm | | | 150mm | | | 200mm | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| Historical | 0.19 | 0.62 | 1.41 | 0.02 | 0.08 | 0.32 | 0.00 | 0.01 | 0.04 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.01 |

The historical return levels are then used to assess potential adjustments to the related reappearance interval (Return Period in years). The colors show, for instance, whether an occurrence that has traditionally occurred every 20 years will occur more frequently (green) or less frequently (brown) in the future. Projections are therefore displayed as future return times (in years) that refer to the current reference point. This future change in return period can also express as a change in the chance of future annual extremes. This product displayed as a factor supplies a potential increase or decrease in the frequency of an event.

**Table 3.** Future Return Period (2010–2039).

| Future Return Period, 2010-2039 (center 2025) (years) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 5-yr | | | 10-yr | | | 20-yr | | | 25-yr | | | 50-yr | | | 100-yr | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| SSP1-1.9 | 2.64 | 4.38 | 6.84 | 4.60 | 8.74 | 15.69 | 7.92 | 17.37 | 37.20 | 9.40 | 21.76 | 49.80 | 15.99 | 43.49 | 129.54 | 26.81 | 88.10 | 376.00 |
| SSP1-2.6 | 2.68 | 4.09 | 6.57 | 4.70 | 7.97 | 14.81 | 8.19 | 15.60 | 34.85 | 9.74 | 19.41 | 46.40 | 16.48 | 37.94 | 118.44 | 27.88 | 74.56 | 327.02 |
| SSP2-4.5 | 2.69 | 4.14 | 7.07 | 4.78 | 8.08 | 16.46 | 8.24 | 15.85 | 38.76 | 9.79 | 19.66 | 51.40 | 16.62 | 38.91 | 129.42 | 27.74 | 77.05 | 348.04 |
| SSP3-7.0 | 2.71 | 4.14 | 6.43 | 4.75 | 8.30 | 14.23 | 8.18 | 16.72 | 32.95 | 9.70 | 20.94 | 44.37 | 16.41 | 41.96 | 118.17 | 27.68 | 84.26 | 336.40 |
| SSP5-8.5 | 2.70 | 4.20 | 6.64 | 4.66 | 8.16 | 14.78 | 7.93 | 15.78 | 34.18 | 9.38 | 19.53 | 45.02 | 15.63 | 38.19 | 109.51 | 25.61 | 74.14 | 285.23 |

**Table 4.** Future Return Period of Precipitation (2035–2064).

| Future Return Period, 2035-2064 (center 2050) (years) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 5-yr | | | 10-yr | | | 20-yr | | | 25-yr | | | 50-yr | | | 100-yr | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| SSP1-1.9 | 2.63 | 4.35 | 6.46 | 4.53 | 8.56 | 14.36 | 7.53 | 17.24 | 33.01 | 8.82 | 21.57 | 43.64 | 14.27 | 43.78 | 110.33 | 22.78 | 89.15 | 325.50 |
| SSP1-2.6 | 2.30 | 3.73 | 6.24 | 3.94 | 7.14 | 13.96 | 6.60 | 13.55 | 32.45 | 7.76 | 16.79 | 43.16 | 12.79 | 32.41 | 109.25 | 20.83 | 62.94 | 286.00 |
| SSP2-4.5 | 2.35 | 3.77 | 6.33 | 3.99 | 7.32 | 14.08 | 6.67 | 14.06 | 33.13 | 7.80 | 17.34 | 44.17 | 12.73 | 33.69 | 111.19 | 20.58 | 66.21 | 299.26 |
| SSP3-7.0 | 2.27 | 3.61 | 5.98 | 3.93 | 6.88 | 13.17 | 6.64 | 13.21 | 30.49 | 7.82 | 16.31 | 40.51 | 12.99 | 31.91 | 102.91 | 21.34 | 62.42 | 289.50 |
| SSP5-8.5 | 2.21 | 3.61 | 5.90 | 3.71 | 6.81 | 12.77 | 6.16 | 12.93 | 29.18 | 7.23 | 15.89 | 38.43 | 11.84 | 30.80 | 93.06 | 18.99 | 59.09 | 238.30 |

**Table 5.** Future Return Period of Precipitation (2060–2089).

| Future Return Period, 2060-2089 (center 2075) (years) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 5-yr | | | 10-yr | | | 20-yr | | | 25-yr | | | 50-yr | | | 100-yr | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| SSP1-1.9 | 2.54 | 4.50 | 8.02 | 4.34 | 9.03 | 19.92 | 7.22 | 18.02 | 47.61 | 8.48 | 22.59 | 65.79 | 13.86 | 44.92 | 188.44 | 22.50 | 91.74 | 597.50 |
| SSP1-2.6 | 2.27 | 3.65 | 6.31 | 3.78 | 6.94 | 14.05 | 6.29 | 13.27 | 32.91 | 7.34 | 16.32 | 43.88 | 11.59 | 31.21 | 113.71 | 18.03 | 60.10 | 331.00 |
| SSP2-4.5 | 2.18 | 3.38 | 6.12 | 3.59 | 6.37 | 13.21 | 5.79 | 12.13 | 29.85 | 6.72 | 14.92 | 39.34 | 10.58 | 28.30 | 95.80 | 16.37 | 53.94 | 243.82 |
| SSP3-7.0 | 1.78 | 2.95 | 5.17 | 2.93 | 5.48 | 10.77 | 4.73 | 10.19 | 23.19 | 5.46 | 12.47 | 29.80 | 8.49 | 23.56 | 67.33 | 13.12 | 44.08 | 163.56 |
| SSP5-8.5 | 1.57 | 2.76 | 5.31 | 2.55 | 4.97 | 10.61 | 3.97 | 9.05 | 22.16 | 4.55 | 11.00 | 28.71 | 6.88 | 20.33 | 69.09 | 10.18 | 37.38 | 174.04 |

**Table 6.** Uture Return Period of Precipitation (2070–2099).

| Future Return Period, 2070-2099 (center 2085) (years) | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Event | 5-yr | | | 10-yr | | | 20-yr | | | 25-yr | | | 50-yr | | | 100-yr | | |
| | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th | 10th | median | 90th |
| SSP1-1.9 | 2.58 | 4.73 | 7.80 | 4.47 | 9.34 | 18.44 | 7.59 | 19.04 | 46.60 | 8.99 | 23.98 | 64.36 | 14.97 | 49.05 | 186.64 | 24.72 | 102.24 | 592.99 |
| SSP1-2.6 | 2.34 | 3.73 | 6.47 | 4.01 | 7.06 | 14.37 | 6.66 | 13.50 | 33.12 | 7.85 | 16.67 | 43.76 | 12.91 | 32.10 | 110.73 | 20.66 | 61.83 | 306.63 |
| SSP2-4.5 | 2.06 | 3.33 | 5.96 | 3.44 | 6.27 | 13.13 | 5.63 | 11.86 | 30.59 | 6.52 | 14.56 | 40.64 | 10.29 | 27.71 | 102.16 | 15.93 | 53.08 | 274.19 |
| SSP3-7.0 | 1.67 | 2.71 | 4.62 | 2.72 | 4.95 | 9.54 | 4.29 | 9.15 | 20.86 | 4.96 | 11.18 | 27.01 | 7.62 | 20.37 | 61.07 | 11.72 | 37.53 | 154.57 |
| SSP5-8.5 | 1.43 | 2.45 | 4.50 | 2.26 | 4.35 | 8.93 | 3.47 | 7.75 | 18.64 | 3.97 | 9.33 | 23.77 | 6.01 | 16.84 | 53.14 | 8.82 | 30.64 | 129.33 |

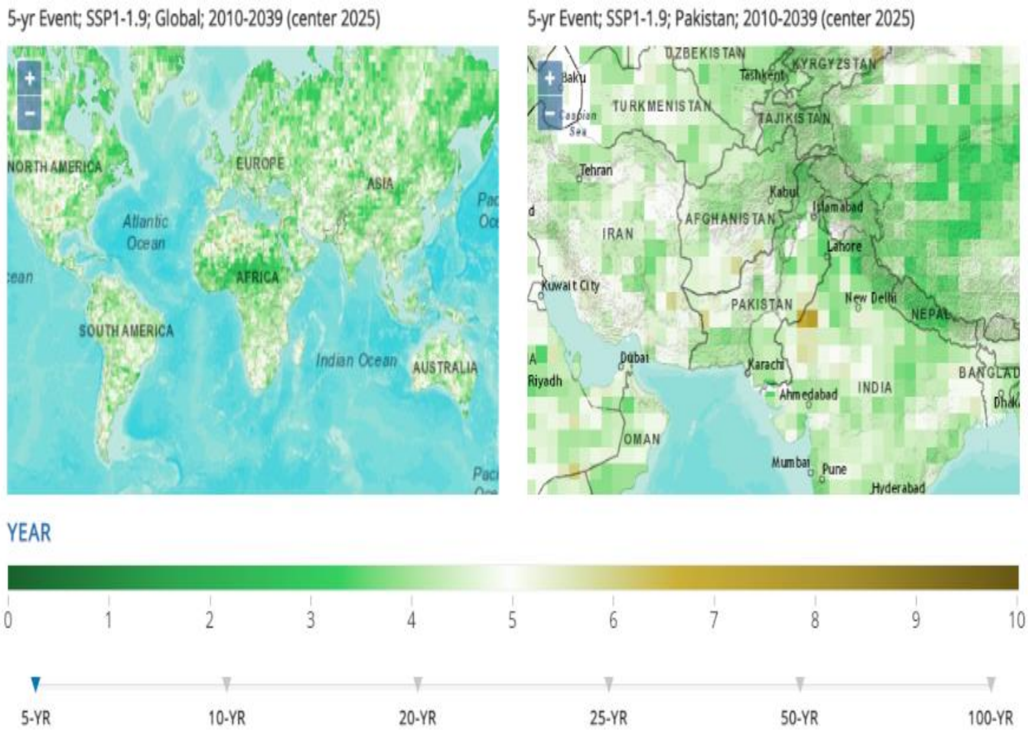


**Figure 3.** Global precipitation from the year (2010–2039).

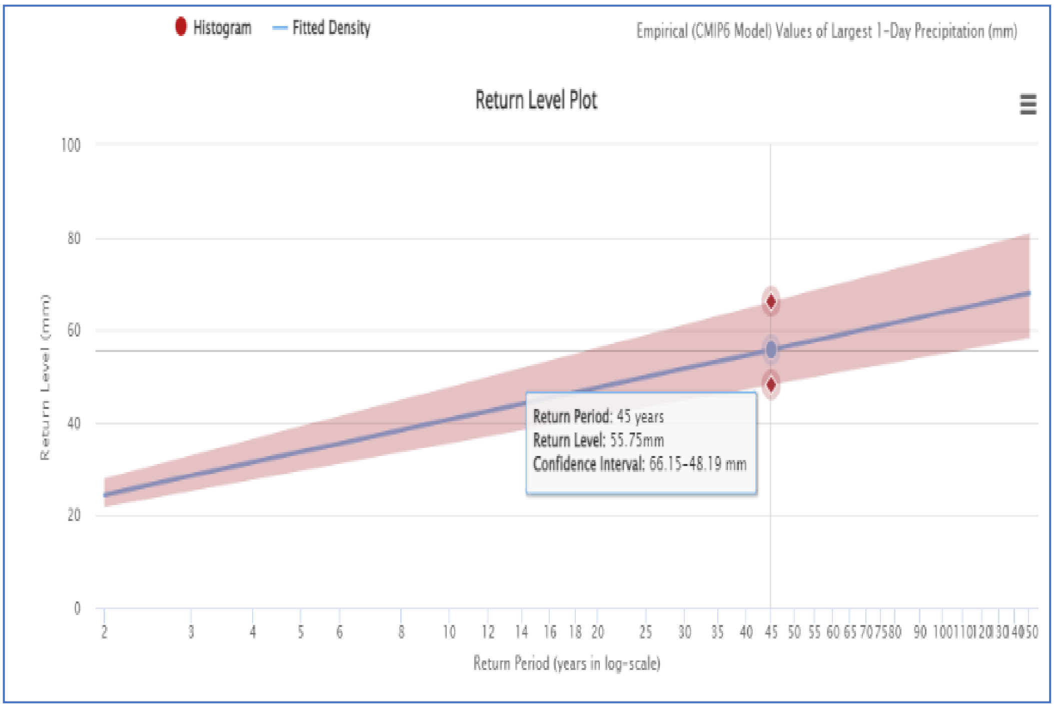


**Figure 4.** Precipitation return level according to long scale.

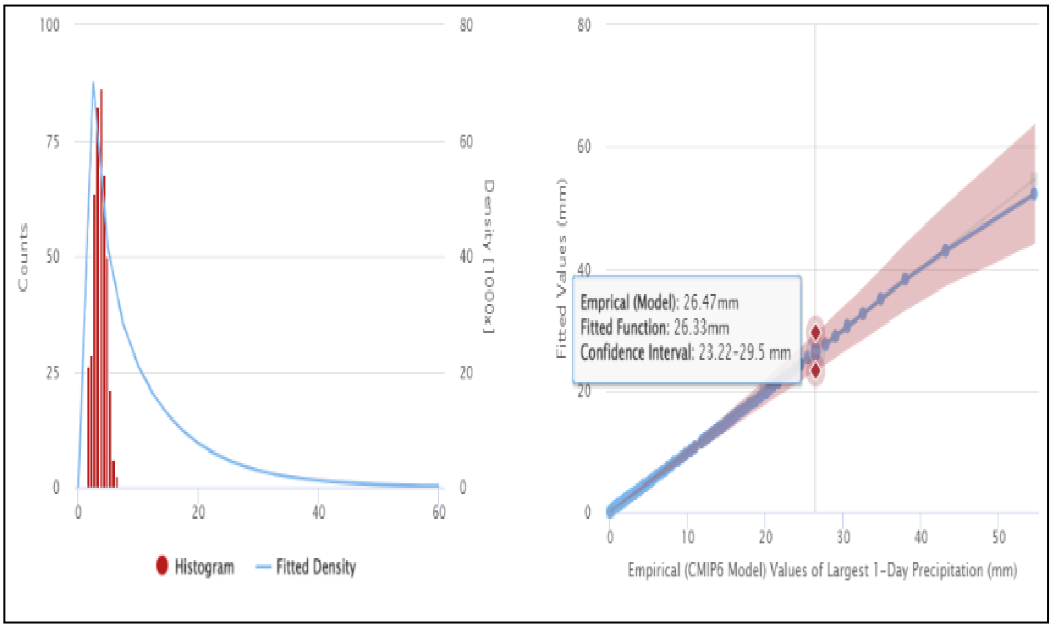


**Figure 5.** Compare Model and observation value of Precipitation.

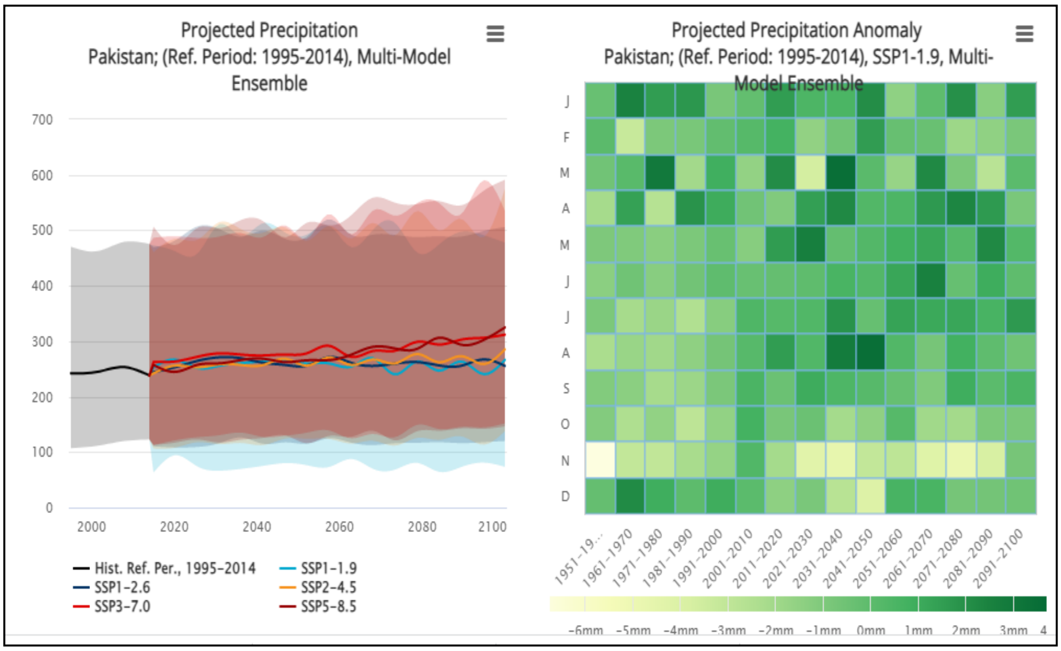


**Figure 6.** Projected Precipitation in Pakistan.

## 4. Conclusions

The flooding was a direct result of the excessive monsoon rain that occurred throughout the summer of 2022, which was made even more by shorter periods of very heavy rain that affected the provinces of Sindh and Baluchistan especially the month of August. Therefore, for the Indus basin and the two provinces, respectively, we evaluate the maximum rainfall over 60 days and over 5 days during the monsoon season.

In the current environment, the return time for both mentioned events are approximately 1 in 100 years. But the amount of rain in the Indus basin varies greatly from year to year for a variety of reasons, including its close relationship to the ENSO cycle. Therefore, precise quantification is challenging.

We compared the trends in climate models with and without the human-induced increases in greenhouse gases to find the contribution of human-induced climate change to these observed changes. The affected areas are in the westernmost extreme o the monsoon region, here the properties of rainfall in the dry western and moist eastern parts differ significantly.

Many of the climate models that are now available have difficulty simulating these rainfall features. The incidence and intensity of extreme rainfall tend to change significantly less for those that pass our evaluation test than the trend we found in the observations. It is impossible to assess the overall contribution of human-induced climate change because of this gap, which points to the possibility that long-term variability or processes that our study may not have considered can have a significant impact.

Our findings are consistent with current IPCC reports.

There is an urgent need to reduce Pakistan's vulnerability to extreme weather according to both the existing situation and the possible future increase in high rainfall over Pakistan because of climate change.

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