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CLIMATE VARIABILITY AND RAINFALL PATTERNS IN PAKISTAN: IMPLICATIONS FOR AGRICULTURE AND WATER RESOURCES

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Abstract

Pakistan is an important region for rainfall, agriculture, water resources, and climatic resilience. However, in the past few decades it has been observed that Pakistan is facing instability, and unpredictability of rainfalls that led to the dramatic manifestation including floods and long spells of droughts. This paper focuses on long and annual rainfall variations between 1991 and 2022 in Islamabad, Lahore and Karachi having variant climate. The study makes use of ground station and statistic evidence to study the annual and the seasonal variation in the monsoon, winter, pre-monsoon and post-monsoon seasons. It is observed that the cities have significant variations; Islamabad holds huge rainfall; Lahore lies in moderate continuous trends and Karachi has low and continuously centered rainfall trends. Research contributes in making effective strategies to manage water resources, agriculture and catastrophes with regards to vulnerability of urban and environmental systems to climate variability.

BACKGROUND

Pakistan also falls into the list of those countries which are highly exposed to the impacts of climate change with little or no contributions to greenhouse gas emissions in the world. The nation had witnessed a number of climate related disasters in the past few decades, especially those caused by abnormal rainfall performances. Extreme weather is reflected strongly by observations on the 2010 mega flood and repetitive droughts, which affected infrastructure, agriculture and livelihoods terribly. Only between 51 and 90 percent of the disasters in Pakistan are climate related, the variability of the precipitation being one of the main factors. Previous trends analysis papers examined the trend with the Mann-Kendall test and Sen estimate industrial slope, which indicated that rainfall

trends change considerably between seasons across the countries. Their evidence included a growing and a declining trend evident in the monsoon and pre-monsoon seasons, respectively, while the winter season signaled a declining trend that affects agriculture and water management systems [1-4]. The more recent study by Ahmad et al. (2023) pointed out the need for high-resolution satellite datasets (such as CHIRPS and PERSIANN-CDR) to address the deficiency in station based rainfall records.

Their analysis in central Punjab showed a definite phase deviation, that is, the rainfall declined until 2001 and upward trends after 2002 with most of the rain occurring in the monsoon season.

It assess the difference in the seasons, and highlight the differences in the regions to help in predicting climates change, planning about agriculture, and governance of water [5].

INTRODUCTION

Pakistan depends heavily on rainfall as part of its climate and environmental system, that affects agriculture, management and control of water resources as well as stability of the entire economy. Being a rain-dependent agriculture country, food security, water supply, and health of the ecosystems in Pakistan are directly associated with the seasonal precipitation spectrum, its timing, amount, and distribution. Nevertheless, within the last few decades, climatic predicaments and weather patterns in the region have led to considerable changes in the rainfall patterns of the country. The trend of seasonal variances has been experienced in Pakistan in the period 1991-2022, which entails a cyclical shift in the monsoon systems, frequent and long periods of drought, and rapid increase of extreme weather patterns, which include city flooding and dry spells [6]. These changes pose risks to agricultural productivity as well as infrastructure, livelihoods and development objectives of the nation. The ability to structure known information on changes in rainfall over recent years, as well as seasonal changes, is one of the conditions for climate resilience building and formulating national adaptation policies. This paper will focus on interpreting the long-term and seasonal data of rainfall trend in Pakistan during the last 32 years have been obtained based on ground observations and the satellite-retrieved ones. The study based on the analysis of the variations in rainfall in winter, pre-monsoon, monsoon, and post-monsoon seasons and changes across different provinces and climatic regions provides thorough grounds to evaluate the changes in Pakistan precipitation patterns. The aim of the findings is to enable data-driven planning in the sphere of agriculture, water management, and climate policy, as well as contribute to the larger picture of the comprehending of climate-induced hydrological alterations in South Asia. The role of the study is to explore long-term and seasonal changes in rainfall patterns in Pakistan in 1991-2022, analyzing spatial and temporal trends in seasonal and regional shifts in rainfall patterns. The study is an extension of existing literature, including that by Ahmad et al. (2023) that examined variability in rainfalls in Central Punjab, by widening the scope to a national level and putting it into perspective of the effects of climate change [7-9].

A. Study Area

This paper focuses on three large cities of Pakistan Lahore, Karachi, and Islamabad, which are situated in different geographical and climatic regions. Eligibility of these cities to be selected was based on population density, economy, and climatic variability which is reflective of the larger hydrological and meteorological regime of Pakistan. Punjab, the

province in Pakistan, has its capital city called Lahore which lies at 31.52 0 N and 74.35 0E and the overall area of the state is 1,772 sq. km. It falls in the semi-arid climatic zone and it is in the fertile plains of central Punjab. Lahore is relatively rainy and that rainfall is mostly concentrated in the monsoon period (June Monsoon September) when almost 6070 of annual rain falls. There are warm summers and mild winters with average temperature fluctuating between 5 than 40 (C) in January and June respectively. As a result of its agricultural and industrial pursuits, rainfall fluctuations have a considerable impact on crop cycles and drainage in the cities as well as in the air. Over the past couple of decades, there is a progressive growth in rainfall amount and number of falls especially monsoon and winter seasons in the region [10-11] Karachi, the biggest city in Pakistan and its economic center is on the coast of the Arabian Sea and is spread over an area of more than 3780 sq.km at 24.86 0 N, 67.01 0 E. It is also in the arid coastal climatic zone which is marked with low rainfalls (100-200 mm), and high temperatures especially in summer. Even though rainfall was not frequent, it was in the form of intense downpours with a monsoon season experiencing most of the intense downpour, However the city falls within the tropical moisture systems and cyclonic activities. In the last decade, flooding on cities has increasingly become a common phenomenon because of heavy torrential rains that last a short time and lack of a well-built drainage system [12-19]. Due to changing atmospheric conditions and growing urbanization Karachi is severely susceptible to hydro meteorological hazards [20-24] located in the geographical region of the foothills of the Margalla hills in the northern region of Pakistan is Islamabad, the capital city of Pakistan, with geographical coordinates of the city being 33.69 o N and 73.06 o east and an area of about 906 sq. km. It belongs to the humid subtropical region and has the warmest mean annual rainfall level of any of the big cities, much of which is contributed by both monsoon and winter rainfall regimes. The city enjoys fairly moderate

weather with the annual mean temperature between 3 ° C and 38 ° C. It is prone to western disturbances due to its altitude and location near the foothills of the Himalayas; therefore, it is one of the main locations to study seasonal variations of the precipitation. The area has been characterized by an upward trend in rainfall particularly the months of post-monsoon and winter period, which carries connotation in terms of water supply, urban planning, and disaster planning [25-26].

This research is a data-oriented study based on the distribution of long-term and seasonal rainfall patterns in three big cities in Pakistan- Islamabad, Lahore, and Karachi- during the duration of the last thirty years between 1991 and 2022. It is a combination of data cleaning, seasonal classification, statistical trend analysis, and visualization with Python and the Scikit-Learn library. A linear regression model was selected in order to examine long-term patterns in rainfall across time. When working with time-based data, linear regression is advantageous because of its ease of use, interpretability, and effectiveness.

Rainfall records for three important cities in Pakistan: [Islamabad, Lahore, and Karachi are included in the dataset. These cities were chosen because of their [geographical variety, climatic variability, and socio-economic significance], all of which support the study's goals of examining Pakistan's seasonal and long-term rainfall patterns (1991–2022). A thorough explanation of the justification for their inclusion is provided below:

1. Islamabad

Climate Zone: Northern, humid subtropical.

Geographic Significance: Islamabad, which lies close to the Margalla Hills, receives (orographic rainfall) that is impacted by monsoons in the summer and western disturbances in the winter. highest yearly rainfall of the three cities, with both winter and monsoonal systems contributing.

Region Selection

Represents the hydrological regime of northern Pakistan, which is essential for the Indus River system's water supply. Indicates increasing post-monsoon and winter rainfall trends associated with climate change (e.g., enhanced western disturbances).

2. Lahore

The climate zone of Lahore is semi-arid, located in the middle Punjab plains.

Geographic Significance: Though susceptible to droughts, the region is dominated by monsoon rains (60–70 percent of annual rainfall). A fertile agricultural area where crop cycles are directly impacted by rainfall variations.

Region Selection

The climate of central Pakistan, a breadbasket area with moderate However increasing rainfall, is reflected in this. Emphasizes urban flooding risks as a result of inadequate drainage and intensifying monsoons.

3. Karachi

Climate Zone: Southern, arid coastline.

Geographical Relevance: Extreme episodic occurrences (e.g., urban floods, cyclonic activity) and minimal yearly rainfall. An economic center with insufficient infrastructure to handle unpredictable weather.

The Arabian Sea's effect (such as tropical moisture and cyclones) is represented by the coastal climatic dynamics. Climate change impacts are demonstrated, such as short duration, intense rainfall (e.g., 2020 floods).

Important considerations for choosing a city include:

Climatic Diversity: encompasses Pakistan's main climatic zones (humid, semi-arid, and desert). The availability of trustworthy long-term ground station records (1991–2022) is the second factor.

Impact on Agriculture and Urban Areas:

Islamabad: Urban planning and water resources.

Lahore: Flood control and agriculture.

Karachi: Economic disruption and coastal resiliency.

Climate Change Indicators: Every city exhibits unique patterns (e.g., increased rainfall in Islamabad vs unpredictable extremes in Karachi).

1. Data Collection and Preprocessing: The data of rainfall was taken by perusal of a structured CSV file (Rainfall dataset improved.csv) which has a list of the daily rainfall observations and identifies a date and city. Pandas library was used to perform the following preprocessing steps:

Dataset Loading: The dataset was loaded without reading the extra metadata lines as it is not required to make the parsing of the dataset accurate.

Date time Conversion: The date column was converted to date time column via pd.to date time and dropped entries that were incorrect to make the data consistent.

Feature Extraction: The columns about the pulse batch and the date of interest were modified, a new column being added that depicts the year and month of the date in order to allow analysis in time dimensions (month and decade). City Filtering: In order to narrow the scope of the analysis, three major urban centers were retained; Islamabad, Lahore and Karachi. String normalization (str.strip() and str.title()) was used to clean the city names.

Chronological Sorting: The data was arranged in orderly manner chronologically so that the events of rainfall could be arranged well in the order of time.

2. Seasonal Classification The data of rainfalls was divided according to the normal South Asian climatology into four meteorological seasons: Winter: December, January, February

Pre-Monsoon (spring): March, April, May

Monsoon (Summer): June to August, September

Post Monsoon (Autumn): October, November A user defined function (get season) was used to map every record to its season based on the column Month

3.Visualization and Data Analysis The labeled and cleaned dataset were then used to calculate average monthly rainfall, seasonal and annual rainfall of every city:

Aggregation: Grouped statistics were developed that grouped the data together in order to calculate the trends of rainfall as time passed using groupby() functions in calculating the trends in rainfall by year and season.

Presentation: A plot of time series was designed through Matplotlib, and Seaborn libraries to illustrate the trend in rainfall between cities and seasons. This visual

investigation allowed seeing trends out above decades and identifying trends in certain periods (e.g., the rainfall is more significant after 2002).

4. Linear regression as Trend Analysis The best way to study long-term tendencies in our rainfall curve over the years was to use a linear regression model which was done using the Scikit-learn library:

TABLE I ORDERAND FRAMEWORKS

Tool/Library	Purpose
Pandas	Data manipulation and preprocessing
Matplotlib	Data visualization
Seaborn	Enhanced plotting and statistical graphics
Scikit-Learn	Machine learning: Linear regression
Python (Jupyter)	Data integration, analysis scripting

Algorithm: Linear Regression model uses sklearn.linear to Inputs: Year which is the independent variable (X), and seasonal / annual average rainfall which is the dependent variable (Y).

Objective The aim was to find out trends of rainfall in either upward or downward direction, per season and per city.

Outputs: The plots of the regression lines against the rainfalls time-series to demonstrate their trends with the coefficients of slopes reflecting the rate of change (e.g. mm/year). This model was applied using city-by-city and season by season in order to get the idea of how the pattern of rainfall has been changing over an incremental period.

5. Order and Frameworks

Such approach has provided the basis of a robust, reproducible and transparent model of examining rainfall variability across major cities of Pakistan and make a connection between statistical trends and their seasonal behavior and possible climate consequences.

III. IMPLICATIONS OF RESEARCH QUESTIONS:

Q1) What general patterns have we seen in Pakistan's yearly and seasonal rainfall throughout the last thirty years (1991–2022)?

The graph shows definite trends in rainfall trends of Islamabad, Lahore, and Karachi:

The annual average rainfall happens in Islamabad every year the highest of all the three cities. Between 1991 and 2000, the amount of rainfall varied between 20-35 per cent RFH. However after 2000 there is a significant rise with annual average going past 40 RFH in more than a few years. This implies that there

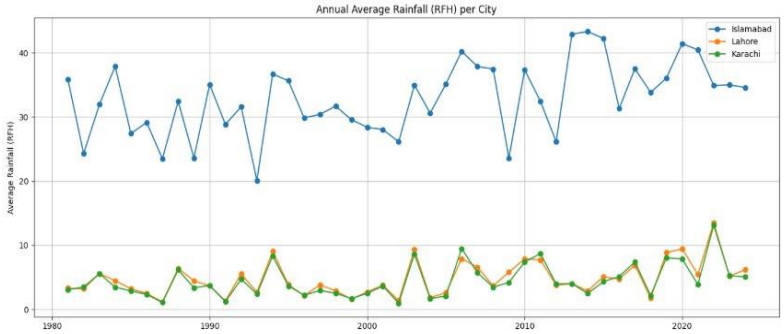


Fig. 1. QUESTION 1 GRAPH

has been a strong increase in rainfall, especially since 2005, which has been oscillating.

Lahore has a moderate precipitation of medium or low range usually between 5-10 RFH and which is also increasing with time. The spikes are present in 1994, 2003, and 2022, which signify that there are some years of heavy rainfalls, still, the overall tendency is rather constant with no big deviations.

Karachi exhibits the worst and unpredictable rainfall pattern. Even though the annual averages remain relatively low? below 8 RFH, there is a sharp spike in some years, namely 2020 and 2022, as a reflection of a recent extreme weather pattern. This follows the trend of erratic and dense precipitation which is in line with increasing urban risks of floods.

Question 2) How have the four seasonal patterns of rainfall such as winter, pre-monsoon, monsoon, and post monsoon had changed over time in Pakistan's various regions?

The Trends in the Post-Monsoon Rainfall:

Islamabad: Exhibits a significant upward trend over the years and with steep surges especially after 2010 that reached their apex in 2014 and once more increase after 2020. It implies that the post-monsoon rainfall pattern in Islamabad is increasing.

Karachi and Lahore: The post monsoon rainfall is very insignificant in both cities with nearly horizontal inclinations with few minor breaks. No pronounced change can be observed in time.

Monsoon Rainfall Trends: Islamabad: Receives the most amount of rains during monsoon in comparison to the other two cities. Although there appears an increase pattern, the recent years appear to show a slight decrease, indicating the weakening of monsoons.

Karachi and Lahore: Both are not extreme in their monsoon rainfall pattern with Karachi featuring a small number of sharp spikes (in 2006 and 2020). There is a steady rise of rainfall in Lahore and this is observed after 2015.

Winter rainfall trends: Islamabad: Has the most con-

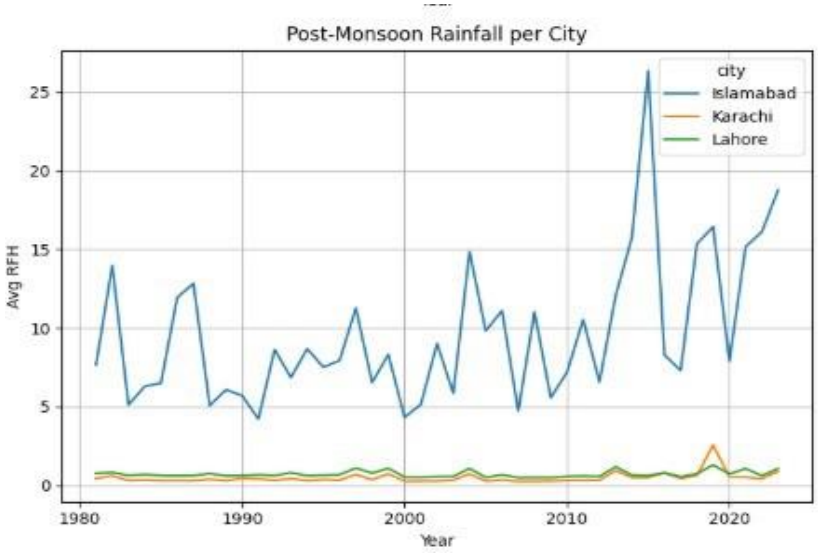


Fig. 2. Question2 Post-Monsoon Rainfall

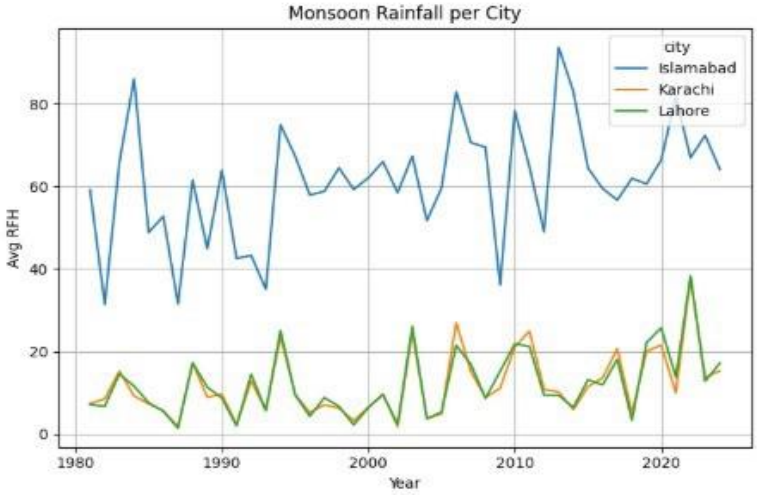


Fig. 3. Q2 Monsoon Rainfall Trends

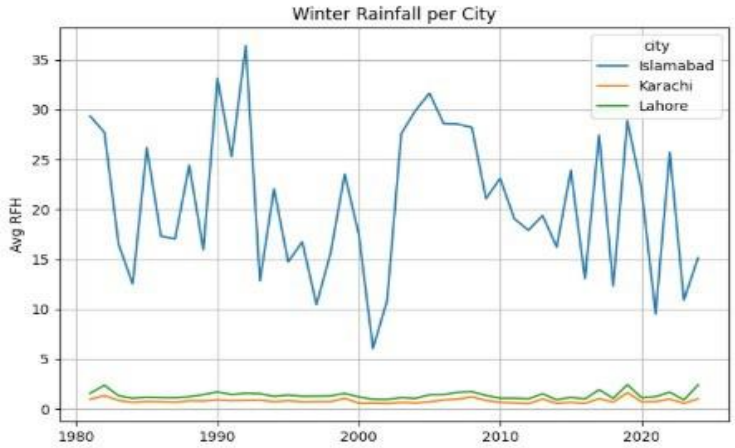


Fig. 4. Question2 Winter rainfall trends

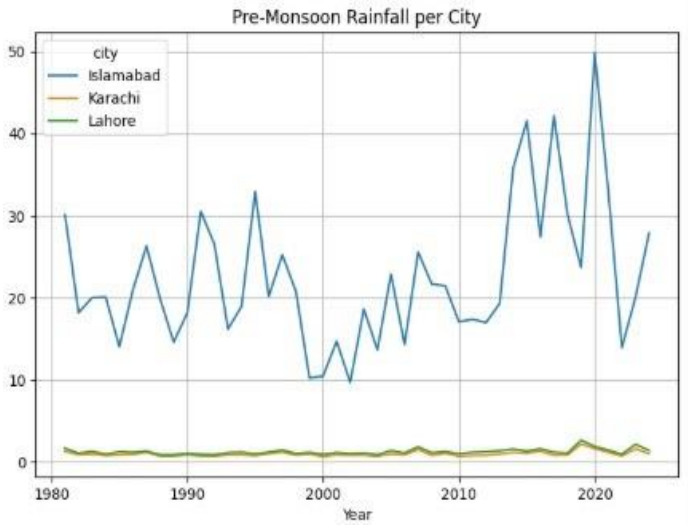
The consistent winter rainfall of all the cities, there is a downward trend registered after the year 2000. The 1980s and the early 2000s have not been maintained at high levels.

3)How has the amount and distribution of rainfall changed over time in major cities like Lahore, Karachi, and Islamabad, and what geographical differences can be observed across Pakistan's various climatic zones?

The visual comparison of monthly rainfall distribution in Islamabad, Lahore, and Karachi; which co-relate to three regions of Pakistan including northern, central, and southern regions. What the analysis demonstrates is as follows:

Islamabad (Humid subtropical/North Zone): Most and most variable rain fall of the three cities. Monthly rainfall is much greater in the median (approximately 3040 RFH) and it also has a wide

interquartile range, meaning that rainfall is usually large over a long period of months. Massive extreme outliers (a data point ¿150-250 RFH) are the indications of the heavy rains and abundantly during monsoon and post-monsoon.



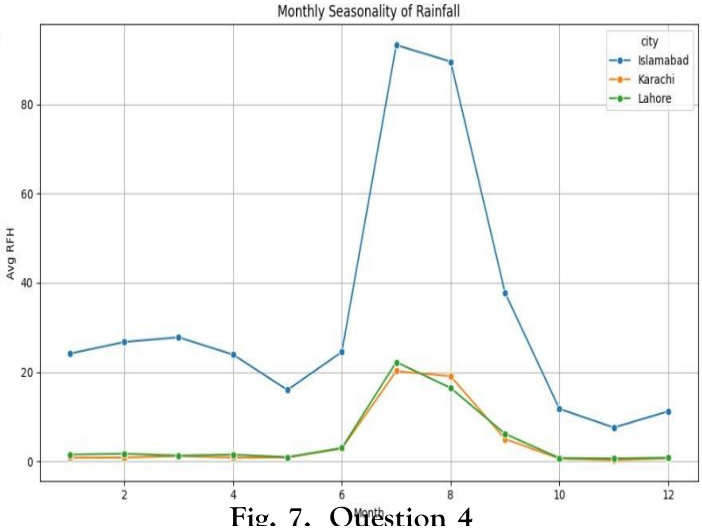


Fig. 7. Question 4

Fig. 5. Q2 Pre-monsoon rainfall

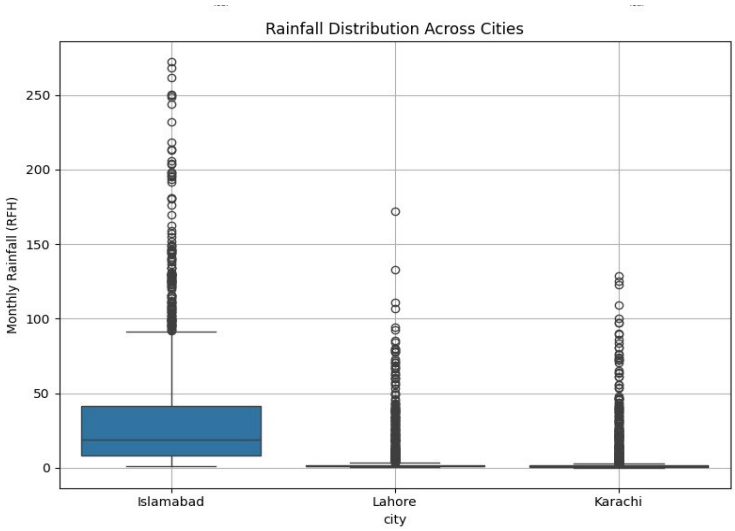


Fig. 6. Question 3 graph periods. This implies that the area of Islamabad has also been receiving not only a substantial amount of rains However also a higher number of extreme weather over the years.

Lahore (Semi-Arid/Central Zone): Much moderate monthly precipitation and a lower median value than in Islamabad. Rain concentration is more biased towards the monsoon season, and smaller outliers, which means that extreme events are fewer. The information shows an intermediate and more steady rainfall trend although to some extent there has been a growing monsoonal rainfall trend over the past years. 3. Karachi (Arid/Coastal Southern Zone): Minimum and densest rain in the three cities. The middle is close to zero which reveals that there are quite a number of parched months which fits the arid climate of Karachi. Nevertheless, the outliers (some above 100 RFH) indicate that Karachi has received the intense rainfalls which are sharp, short-lived, probably because of the urban flooding and coastal meteorological systems, particularly in the recent years.

It is interesting to note an irregular, wave-like trend where periodic rainfalls during some seasons would be ignored in favor of high-intensity rains.

4) In what ways do Pakistan's rainfall patterns correspond with the possible effects of climate change? The graph is good source to show how very acute season concentration of precipitation is when Islamabad in the month of July and August enjoys sweeping over 90 RFH and the same case applies to Karachi and Lahore which also receives its highest precipitation in July and August months. This is one of the trends that shows several impacts that might be produced by climate change:

1.Monsoon Rains Intensification Based on the graph, it has been revealed that it rains within 2-3 months and the level of precipitation is very high on the side of Islamabad. It is the symptom of a lessened, more dangerous monsoon season which is the characteristic climate change symptom all across South Asia. Fewer days and larger amounts of rain that are less continuous than during a season are falling more and more and that fact breeds the chances of urban flooding and flash flooding.

An Increased Seasonal Imbalance The months which are not a part of monsoon (September-June) have extremely low rainfall especially in Karachi and Lahore which may be a sign of lengthy drought followed by utter wet state. It is the manifestation of the widespread climate patterns of climate excesses in which wet areas are made wetter and drier areas more dry across the world.

Inequality in Climate Response at Gross Regional Level Islamabad as contrasted to Lahore and Karachi experience a lot of rainfall all the year round and therefore north of the country can be affected by augmented western disturbance and orography perturbations. The Karachi coast climate is arid with fewer and less frequent rainfall which could imply shift in the increasing sea surface temperature and the tropical weather phenomenon.

Popularity of Rain Precipitation Shift In comparison of the scenario with the historical events it can be imagined that due to the present maximum and the volume of the monsoon rainfalls especially that of Islamabad there might be a change

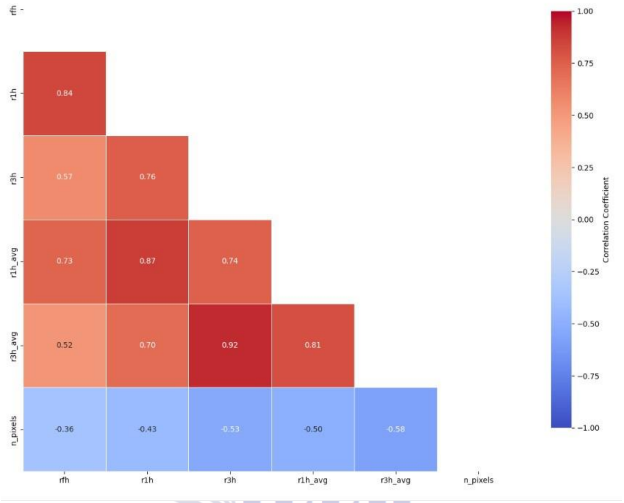


Fig. 8. The heatmap for aggravation of the monsoons systems- an established effect of global warming in the region.

Based on this graph, this fact can be corroborated that this is where the pattern of rainfall in Pakistan is increasingly relying on climate changes-will bring more intense monsoons, prolonged dry spells, geographical imbalance, and enhanced variability. The events are good reminders that the world requires resilient infrastructural systems in terms of climate, city drainage systems, and intelligent water resources.

IV. DISCUSSION

Discussion The trend of long-term and seasonal rainfall in major cities of Pakistan (Islamabad, Lahore, and Karachi) indicates that only a few regions in the country have experienced an increase in rainfall, whereas an excellent temporal and spatial distribution of rainfall has been observed across all cities of the country. Such results point to the increased impact of climate change, urbanization and climatic change in regions on the hydrological processes of the country.

A. Climate zones and Regional Variability Regions

Islamabad in humid subtropical area observed the maximum rainfall at all times with summer and winter seasons playing their part. Through the data, there is increasing trend of annual and post monsoon rainfall especially after 2005, which can be attributed to the global warming trend and the rising capacity of the atmosphere to carry moisture. These upward trends are probably related to the response between the western disturbances and strengthened monsoonal systems.

The city of Lahore located in the semi-arid region showed fairly stable However marginally rising rainfall patterns in particular monsoon and the winter

months. The pattern shows slow changes in the climate of Central Punjab, modest seasonal changes which have significant impact on agriculture, floods in towns and planning of water resources.

Karachi, however, had the most unpredictable rain fall patterns. Being the arid coastal city, even the minimum rates of precipitation are minimal, recent years were characterized by dramatic jumps in rainfall levels, especially 2020 and 2022. Such violent and brief rainfalls have resulted in floods happening quite often in the city. These 3 factors, with long range effects on the coastal cyclonic activity, shifting sea surface temperature, and ineffective management of the urban infrastructure, explain the rhythmicity and concentration of the rainfall in Karachi.

B. Seasonality and extreme events

The study finds that monsoons season has remained dominant in annual rainfall pattern in all the three cities and this plays a key role in giving rise to more than 70 percent of the total rainfall in a year. However there was a note of rising trends of post-monsoon and winter rainfall, especially, in case of Islamabad and Lahore. The change is indicative of a lengthening of the rainy season, which may be as a result of late withdrawal of monsoon winds and continued western weather patterns. Classically, the central and southern sectors experienced minimal winter rains However evidence shows that this region is experiencing a continuous increase, possibly due to the diversion of the jet streams and the enhancement of westerly-a wave of occurrences. Such developments are necessary because they can influence the schedules of crops, irrigation and replenishment process of the ground water during the off-months of the rain.

C. There is an implication of Water Resource and Urban Planning.

The policy implications of the results are important to climate adaptation policies. In Islamabad the necessity to improve flood and drain control can be due to a continually increasing rainfall amount over there although on the

other hand Lahore is requiring moderate and steady increase which requires improved urban water management. The means of countering an occasional emergency flood because of the low frequency and high frequency of low-frequency reasons of flooding should have a good early warning system and enhanced storm water system in Karachi. The regional peculiarity of the climate resilience approaches demonstrates the importance of the climate resilience strategies differentiation as applied to the cities too. The generic strategies may not be of much help since the northern regions, the central regions and southern regions are like poles apart in the way they manage the rain that falls.

D. In Support of the Climate Models and the Past Research

The results of these studies are consistent with other studies of earlier scholars such as the study carried out by Ahmad et al. (2023) have shown that trends in rainfall are rising in the area of Central Punjab. This work is an extension of such works in that it takes into account the satellite information and operationally upscale the work that climatic variability is no longer a nightmare of far corners, it has become a national problem.

The frequency, intensity and the distribution of rainfall has started to change in Pakistan. Although in some areas there is a general trend of extreme variability of precipitation, the total amount of it increases. These changing trends are vital in comprehending agriculture, disaster preparedness, and sustainable water management in a water-sensitive and climate-prone country in Pakistan.

V. FUTURE WORK

The research study revealed helpful information regarding to rainfall patterns in the major cities of Pakistan, much can be learnt. The future research would be better in the following ways:

Saying adding cities and rural areas to the national picture so as to have a comprehensive approach to the national rain fall behavior.

The objective of the paper is to discuss the impact of climate change on the water cycles focusing on temperature, humidity, and evapotranspiration as the larger panorama of rainfall. Using the machinery learning or AI -based algorithm to come up with a correct prediction about the future weather pattern and extreme weather events level.

The correlation of the rainfall trend and the agricultural production level only reflects that in major agricultural areas rainfall change of intensity is significantly influencing the agricultural production. Application of social and economic data to establish how the change in trends of rainfall has affected the infrastructure in the city setting, the livelihood among the rural regions of the globe and the threat of floods. Jobbing through climate scientists and urban planners on collaborative formulation of the policies necessary to deal with water resources management and resilience to the climate changes.

As this study entails one of the grounds to find a lie when defining the additional work, it will be possible to orient Pakistan in a better way against the changing climate and its influence on the environment in the future.

VI. CONCLUSION

This study investigates evolutions in rain in the past three decades over three cities among which is Islamabad which acts as an example of the fluctuations that have occurred in climate within the Pakistani country. The rest are Lahore and Karachi. The trends are certain in the results: There was also greater amount of rain in the city of Islamabad and it was heavier than other seasons such as monsoons and tides. There were moderate changes reported in Lahore with increase recorded in rainfall that has remained stagnant and pertinent during winters and summers. The one that was most unpredictable was Karachi which has a general dry character However at some instances there would be torrential precipitation.

The trends indicate how the patterns of rainfall in the country are being altered by differences in climates in that the amount of rainfall is increasing more than before in certain regions as compared to others that are suffering extreme events whose occurrence is not regular. Such changes are therefore relevant in flood monitoring and control, farming, city infrastructural planning and water resource management. Research that is required to adapt the cities and communities in Pakistan is the kind that has to be undertaken as it addresses more and more issues that are being related to climate, each day. As the remainder of the research progresses, and as the research community proceeds effectively with the execution of their plans, it is possible to transform such realizations to meaningful intercession in direction to a fairer climate in the future.

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