INVESTIGATION OF CAUSES AND CHARACTERISTICS OF MONSOON EXTREMES IN PAKISTAN: A CASE STUDY FOR SUMMER MONSOON 2022

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ABSTRACT

Apart from the long-term changes in the climate patterns, the extreme weather conditions (heat waves, heavy precipitation, and droughts) have also emerged as a prominent consequence of the global climate change. Pakistan being listed among the most susceptible nations to the changing climate patterns has witnessed an increasing trend of extreme precipitation (particularly during monsoon). Therefore, this study was conducted to probe the major meteorological causes of extreme monsoon precipitation in Pakistan, with a special focus on the monsoon 2022, that lead to severe flooding and devastation of infrastructure, agriculture, and loss of lives. The methodology included an in-depth analysis of unusual atmospheric conditions that triggered exceptionally high precipitation. For this purpose, a number of 25 stations across the country lying in the southwest monsoon zone were selected.

The analysis revealed that in April 2022, about 1.2 to 6.0 °C above normal temperature was observed in Balochistan, 2.0 to 4.5 °C in Sindh, and 3.0 to 5.8 °C in Punjab and KPK. Similarly, in May, about 1.0 to 3.5 °C above normal temperature was observed in Sindh and Balochistan, and 1.0 to 3.0 °C in Punjab and KPK. Due to this exceptional warming, an intense trough developed over the area. In April, about 0.5 to 2.5 mb below normal air pressure was observed in Sindh and Balochistan, and 1.5 to 2.2 mb in Punjab. In May, about 1.0 to 3.0 mb below normal air pressure was observed over the study area. For precipitation, the analysis unearthed that in July 2022, about 100 to 300 mm above normal monthly rainfall was received in Sindh, 50 to 200 mm in Punjab and Balochistan, and 5 to 30 mm in KPK. In August, about 100 to 500 mm above normal rainfall was received in Sindh, and 50 to 250 mm in KPK and Balochistan. However, in September, about 15 to 75 mm above normal rainfall was received in Punjab, while the remaining stations showed a negative departure. Conclusively, the unusual pre-monsoon heating resulted in an intense depression over the plains that facilitated the excess moisture penetration from the Indian Ocean, and consequentially extreme precipitation in Pakistan in 2022. The study outcomes are expected to help in devising an effective climate change adaptation and mitigation strategy for the country and to conduct further research on the prediction and analysis of extreme weather conditions under the changing climate patterns.

Keywords: Climate Change, Extreme Precipitation, SDG13, Southwest Monsoon, Temperature

1.0 INTRODUCTION

The occurrence of extreme precipitation events has gained much momentum around the world during the past decades as a consequence of the changing global climate patterns. Climate change generally refers to the long-term changes in the normal weather patterns of an area [1, 2]. These long-term changes are mainly caused due to the anthropogenic activities including land cover alterations and sprawling urbanization, declining forest cover, and emission of toxic greenhouse gases into the air which destabilizes the global heat balance (a balance between the incoming shortwave and the outgoing longwave solar radiation) by trapping the outgoing solar radiation [3]. This trapping of the outgoing heat leads to the warming earth temperature, which consequently results in the changing atmospheric and land surface conditions [4, 5]. Among all weather parameters, air temperature is generally considered to be the most influential on the overall climate pattern of an area, as it significantly impacts (accelerates) the hydrological cycle by expediting the movement of water vapors from land to atmosphere (via increased evapotranspiration), and also influences the other components of weather system including the air pressure gradient and wind circulation, evaporating potential of atmosphere, air moisture availability, cloud cover, and the precipitation characteristics [6]. During the last century, the mean global air temperature has increased by about 0.74 °C [7, 8], whereas regionally, the mean temperature over South Asia rose by about 0.75 °C [9]. Due to the rising earth temperature and changing wind circulation and other atmospheric variables, the precipitation patterns have undergone significant variations around the world. For instance, during the last century, the mean global land surface precipitation increased at the rate of about 0.04 inch/decade [10, 11]. However, due to the highly variable nature of precipitation, and due to its high sensitivity towards the spatial features of an area, some regions of the world also witnessed a declining precipitation. For example, Alahacoon *et al*. (2020) used the Mann-Kendall test to investigate the rainfall trends in the African continent, and found a declining precipitation pattern in Mozambique, sub-tropical northern desert, west coast river basin of South Africa, and the northern African region, at the rate of about 0.437, 0.80, 0.360, and 1.07 mm/year respectively [12]. Merabtene *et al*. (2016) studied the rainfall patterns in Sharjah (UAE), and found a negative trend of annual rainfall at the rate of about 3 to 9.4 mm per decade [13]. A similar nature of trend was found in a study conducted by Almazroui (2020) in the Kingdom of Saudi Arabia (KSA), according to which the annual mean rainfall declined at the rate of about 5.89 mm/decade during the last four decades over the country [14].

Apart from the long-term changes in the precipitation patterns (form, amount, seasonality, and its spatial coverage), climate change has also impacted the intensity and extremity of precipitation around the globe. A high intensity precipitation generally refers to the large amount of precipitation received over an area in a short period of time [15]. During the past decades, the frequency of occurrence of high intensity extreme rainfall events has increased globally, mainly due to the warming air temperatures, as the warm air can hold more water vapors in it as compared to the cold air, and the availability of water vapors serves as the key ingredient for heavy rainfall [16]. According to the Center for Climate and Energy Solution, for each degree centigrade rise in air temperature, the air water holding capacity can increase by about 7% on average globally [17]. Thus, the warm areas are more prone to the intense storm events as compared to the cold areas [18]. Another atmospheric parameter which significantly influences the wind circulation and the precipitation characteristics is the air pressure, which strongly depends on the air and land surface temperatures and the geographical location of an area. Due to the differential solar heating of the earth surface, a noticeable latitudinal variation in the air pressure exists around the globe known as the Pressure belts, which facilitate the global wind circulation [19]. In general, winds follow a pressure gradient, and are blown from a high pressure area to a low pressure area, with greater the pressure gradient, the more will be the wind velocity [20]. These High and Low Pressure Systems (HPS and LPS respectively) are mainly characterized on the basis of air temperature and wind circulation. Warm areas generally result in the formation of LPS (also known as Depression or Cyclone), characterized by high wind convergence towards its center, higher cloud cover due to the rising moist air and condensation, and heavy precipitation due to sufficient availability of moisture and convergence of air masses [21]. Moreover, in warm areas, winds blow spirally in the counter-clockwise direction in the Northern Hemisphere and clockwise in the Southern Hemisphere due to the Coriolis Effect [22]. On the other hand, cold areas generally result in HPS (also known as Anticyclones), characterized by fair weather and moderate winds blowing spirally outward in a clockwise direction (Northern Hemisphere), low cloud cover, and less precipitation [23]. A weather condition which is formed due to the intense heating of land surface is known as the Thermal low, Heat low or the Trough. Around the world, the strongest thermal lows are developed over the Sahara, Australian Great Western Deserts, Arabian Kalahari, and Sonoran Deserts due to the intense surface heating [23]. It is important to note that lower the air pressure, the higher the warm air containing moisture will rise into the atmosphere and form clouds after condensation of water vapors in air, with the greater probability of intense storm events [24, 25].

During the recent past decades, a number of intense rainfall events have been observed over the different parts of world, as a consequence of warming temperatures and changing global air circulation patterns. For example, in summer 2020, the Baixada Santista metropolitan region in the Sao Paulo state of Brazil received about 320 mm of rainfall in a single day, breaking the country's previous highest 24-hr rainfall record [23]. Similarly, in 2022, Taiwan received the third highest winter rainfall in the country's history during January to February. As per Huang *et al*. (2022), Taiwan normally receive its winter rainfall from the precipitation system originating in the northern South China Sea without frontal structure. However, in the year 2022, contrary to the normal rainfall pattern, the winter monsoon induced orographic rainfall penetrated the country along with the frontal rainfall, thereby bringing about 130% higher rainfall than the normal. The occurrence of this extreme storm event was also linked to the enhanced winter background circulation, which included an enhancement of the regional northeasterly wind at 925 hPa in conjunction with the enhancement of the southwesterly wind conveying moisture at 700 hPa, due to which a vigorous convection zone extending from the southeastern Bay of Bengal to Taiwan was censured for the extreme rainfall in January to February 2022 [26]. A similar 24-hour extreme rainfall event was witnessed in Auckland (New Zealand) on 14th January 2023, when the city received about 258 mm of rainfall, making it the wettest day in the city on record with the total rainfall of about 539 mm was received in January over the city [27].

The word "Monsoon" generally refers to the seasonal change in the prevailing wind pattern due to the temporal latitudinal shifting of the Intertropical Convergence Zone (ITCZ) between its extreme limits as the Tropic of Cancer (23.5 °N) and Tropic of Capricorn (23.5 °S) in the northern and southern hemispheres respectively [28]. Globally, the major monsoon systems include the African monsoon, Asian monsoon, North American monsoon, Australian monsoon, and the European monsoon [29]. The Asian monsoon has two branches as the South Asian monsoon and the East Asian monsoon [30]. The South Asian monsoon covers the Indian sub-continent and the surrounding regions including Nepal, Myanmar, and Bangladesh, whereas the East Asian monsoon covers southern China, Korea, Taiwan, and Japan [31]. Based on the seasonal wind pattern, the South Asian monsoon is further divided into two categories as the Southwest Summer monsoon (advancing monsoon) and the Northeast Winter monsoon (retreating monsoon) [32]. Pakistan receive its summer precipitation from the southwest summer monsoon during July to September, which contributes about 60% to the country's annual total precipitation, and holds a significant importance in terms of the replenishment of streamflows and groundwater resources, and favoring the Kharif crop production [33].

The major factors which govern the mechanism of the southwest summer monsoon system include the differential heating of the land mass in the Indian sub-continent and the Indian Ocean, development of a high pressure system over the Indian Ocean, seasonal latitudinal shifting of ITCZ at the Tropic of Cancer, formation of Tibetan trough, Sub-Tropical Westerly Jet Streams (STWJ) and the Tropical Easterly Jet streams (TEJ), and El-Nino Southern Oscillation (ENSO) [33, 34]. In South Asia, the southwest summer monsoon system generally initiates with the differential heating and the development of air pressure gradient between the Indian Ocean and the land masses in India and Pakistan. With the onset of summer season in the northern hemisphere, the Thar desert and the nearby warm arid and hyper arid plains in India and Pakistan warms up more quickly as compared to the Indian Ocean, due to the fact that the rate of heat absorbance of soil surface is higher than that of water. Due to this differential heating, a high pressure system called as the Mascarene high is developed over the Indian Ocean (between the latitudes 30 to 35 °S and between the longitudes 40 to 90 °E) along the eastern coast of Madagascar, while a low pressure system is developed over the landmasses due to the higher surface heating. This air pressure gradient created between the plains and Indian Ocean results in a strong moist wind system originating from the Indian Ocean (Madagascar region), that starts to march towards the equator in the northwest direction, and after crossing the equator, the wind system is diverted, and it blows from the southwest direction towards the southern Indian peninsula, where due to its topography, the southwest monsoon system is divided into its two branches as the Arabian sea and Bay of Bengal in the Indian Ocean [35, 36].

Due to the seasonal latitudinal shifting of ITCZ at the Tropic of Cancer during summers in the northern hemisphere, an intense heating takes place over the Tibetan plateau, which results in the formation of LPS over the area, known as the Tibetan trough. This LPS also plays an important role in pulling the moist monsoon winds from the Arabian Sea and Bay of Bengal towards the land areas of India and Pakistan. In addition, the latitudinal shifting of ITCZ and heating of Tibetan plateau also impacts the pattern of jet streams in the region. For instance, the sub-tropical westerly jet streams normally travel in the upper troposphere from west to east, closer to 30 °N along the southern edge of Himalayan range all over the year. However, with the onset of summer season and shifting of ITCZ in the northern hemisphere, STWJ is displaced towards the northern Himalaya. The Himalayan belt also impacts the incoming moist monsoon winds from the Bay of Bengal by acting as a physical barrier and preventing the monsoon incursion into the Central Asia. Due to the seasonal heating of Tibetan plateau and formation of Tibetan trough, the warm air over the area rises up and cools as it reaches the upper troposphere, resulting in the formation of a high pressure system (approximately 200 hpa) over the altitude, which weakens the blowing STWJ over the northern Himalaya and results in the formation of Tropical Easterly Jet streams (TEJ) on the southern side of the high pressure system. This TEJ then moves westward over the Indian Ocean towards the eastern Africa and descends into the Mascarene high, thereby strengthening the high pressure cells of the Madagascar high pressure system. It is important to note that the intensity and location of Mascarene high significantly impact the strength of monsoon rainfall system in India and Pakistan [37, 38]. The monsoon precipitation typically begins from 1st June in India, and then the rainy system enters Pakistan on the first week of July. In Pakistan, the southwest monsoon system penetrates the country via its two branches, i.e. the Arabian Sea and the Bay of Bengal. The monsoon rainfalls in Pakistan generally starts with the moisture carrying wind system coming from the Bay of Bengal, which enters the country from the eastern and northeastern side, and results in generous rainfall over the northern areas, northern and central Punjab, and Kashmir. The other branch of southwest Monsoon i.e. the southwesterly moist winds from the Arabian sea then enters Pakistan, and brings good amount of rainfall over the southeastern parts of country including Sindh and Balochistan [39].

As discussed earlier, the El-Nino Southern Oscillation (ENSO) also influences the South Asian Monsoon [40]. For instance, the El-Nino which is the warmer phase of the El-Nino Southern Oscillation (ENSO) and generally takes place due to the unusual warming of sea surface temperature of the eastern Pacific Ocean along the South American coast, adversely affects the monsoon precipitation in Pakistan and India by causing drought conditions. This is due to the fact that during El-Nino, the air moisture from the Mascarene high is diverted towards the eastern Pacific Ocean due to the formation of an intense low air pressure condition over the eastern pacific along the coast of South America [41]. In Pakistan, the history's worst drought during 1998 to 2001 was mainly attributed to El-Nino. In contrast to El-Nino, La-Nina, which is the cooler phase of ENSO, brings above normal Monsoon precipitation. For example, the 2010 extreme Monsoon rainfalls in Pakistan was mainly linked to the occurrence of La-Nina [42, 43].

1.1 Literature Review

Synchronously to the changing global climate patterns, the weather patterns in Pakistan have also undergone significant variations over the years. For instance, the mean annual temperature of Pakistan increased by about 0.64 °C during the period 1900-2009, at the rate of about 0.064 °C per decade [44]. Interestingly, the rate of warming was higher during the latter part of century as compared to the earlier years over the country, which was reported in a study conducted by the Asian Development Bank, according to which the mean annual temperature of Pakistan increased at the rate of about 0.07 °C per decade during 1960-2021, with the magnitude of change as 0.47 °C during the period. Seasonally, the warming trends in Pakistan have been found to be more inclined towards the spring, post-monsoon, and the winter months, as compared to the summer season [45, 46]. Due to the warming air temperatures, and the consequential changes in the air moisture conditions and wind patterns, the frequency of short duration extreme rainfall events has significantly increased in the country during the past decades, as shown in the Figure 1. For example, on 23rd July 2001, about 621 mm of rainfall was received in Islamabad in 10 hours, thereby causing severe urban flooding in the city. Similarly, on 18th July 2009, about 207 mm of rainfall was received in Karachi, making it one of the highest one-day rainfall recorded in the city [47]. On 19th August 2022, Padidan received the record breaking 355 mm of rainfall due to the formation of intense low air pressure conditions over the northern belt of Sindh province (*PMD Annual Climate Report,* 2022). The details of some of the 24-hour extreme rainfall events that took place over the country during the past 30 years are shown in Table 1.

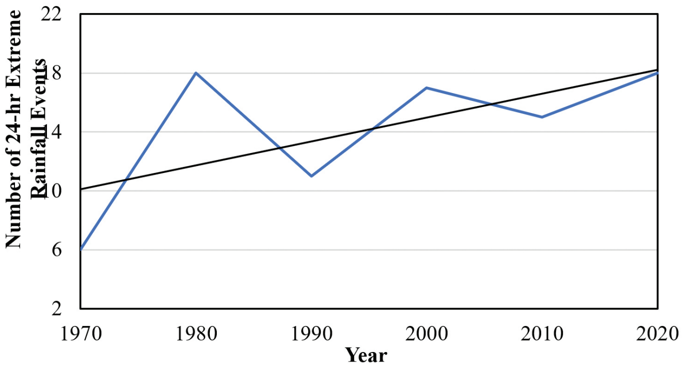

Figure 1: Frequency of Occurrence of Extreme Rainfall Events in Pakistan with Rainfall Above 200mm Received in 24 Hours

Source: Pakistan Meteorological Department (PMD)

The above statistics clearly indicate that the occurrence of extreme rainfall events has significantly increased in Pakistan, especially during the monsoon season. For instance, in 2003, Sindh received above normal monsoon precipitation, which resulted in severe flooding in the province. During the two-day rainfall spell, 284.5 mm of rainfall was received in Karachi, and 404 mm in Thatta. In 2007, Khyber Pakhtunkhwa (KPK), Sindh, and the coastal belt of Balochistan was severely affected due to the extreme monsoon rainfall. In 2009, Karachi received 147 mm of rainfall during 17th to 19th July, which resulted in severe urban flooding in the city. In 2010, Pakistan faced the worst flood in its history due to the occurrence of extreme monsoon precipitation (80% above normal) over the country that inundated about 20% of its land area [43]. The post event analysis by PMD revealed that the above normal rainfall was mainly caused due to La-Nina. The other contributing factors included the unusual change in the position of monsoon depression formed over the Bay of Bengal, that moved towards the northeastern side in Balochistan and caused a large amount of moisture incursion from the Bay of Bengal and Arabian sea, and then its convergence over Khyber Pakhtunkhwa due to the orographic effect, thereby causing extreme precipitation over the area. The spatial features of the flood-hit areas also played a significant role in the convergence and lifting of water vapors. In this context, near to the middle troposphere, the cold air advection from 500 mb occurred over the Pakistan's latitudes, and the lower elevated warm and moist air was overtaken by the cold air mass which created an intense cellular vertical circulation. This resulted in a continuous incursion of moisture from both branches of southwest monsoon. Moreover, the presence and stagnancy of STWJ over the northern Pakistan was another factor which played a significant role in the incursion and movement of water vapors over the higher latitudes of country, which resulted in extreme precipitation. As per PMD, during 27th July 2010 to 30th July 2010, 415 mm of rainfall was received in Risalpur, 394 mm in Islamabad, 373 mm in Murree, 372 mm in Cherat, 333 mm in Peshawar, 292 mm in Muzaffarabad, 256 mm in Balakot, 222 mm in Gujranwala, 220 mm in Dera Ismail Khan, and 219 mm was received in Rawalpindi. Comparatively, the monthly rainfall in July 2010 was 80% above normal, while in August, 102% above normal rainfall was received in the country. The intense rainfall induced floods caused approximately $43 billion loss to the national economy, 1700 loss of lives, and damage to about $500 million worth of crops [48].

Table 1: Details of 24-Hour Extreme Rainfall Events in Pakistan During the Last 30 Years

Source: Pakistan Meteorological Department (PMD)

Date	Station	Rainfall (mm)
10th September 1992	Muzaffarabad	208
27th August 1997	Islamabad	200
27th August 1997	Murree	233.8
24th July 2001	Islamabad	200
23rd July 2001	Rawalpindi	335
7th July 2003	Larkana	209
29th July 2007	Sargodha	205
13th August 2008	Lahore	221
18th July 2009	Karachi	205
29th July 2010	Risalpur	280
29th July 2010	Peshawar	274
30th July 2010	Islamabad	257
29th July 2010	Cherat	257
29th July 2010	Kohat	233
30th July 2010	Murree	231
6th June 2010	Gwadar	227
4th August 2010	Dera Ismail Khan	202
11th August 2011	Tando Ghulam Ali	350
7th September 2011	Diplo	312
10th August 2011	Mithi	291
26th August 2011	Kohat	240
31st August 2011	Padidan	238
7th September 2011	Mithi	225
11th August 2011	Tando Muhammad Khan	200
11th August 2011	Tando Ghulam Haider	200
10th September 2012	Jacobabad	305
5th September 2014	Lahore	300
5th September 2014	Jhelum	296
5th September 2014	Islamabad	297
5th September 2014	Mangla	251
5th September 2014	Sialkot	251
2nd September 2020	Bahawalnagar	240
28th August 2020	Karachi	231
19th August 2022	Padidan	355
25th August 2022	Shaheed Benazirabad	123
22nd August 2022	Larkana	157.3
6th July 2022	Gwadar	58
27th July 2022	Ormara	62
22nd July 2022	Rahim Yar Khan	58

In 2011, the situation was different as the extreme monsoon precipitation was mainly concentrated in Sindh, unlike in 2010 that affected KPK and Punjab. In July 2011, Pakistan as a whole received below normal rainfall. However, in August and September, the country received more than average rainfall [49].

As per PMD, a strong weather system was formed over Uttar Pradesh in India on 6th August 2011, which then moved in the westward direction. The first healthy spell of summer monsoon began lately in the country from 9th August as a result of deviation of monsoon depression from its usual route. Normally, the southwest monsoon system enters Pakistan from the northeast, and rainfall begins with the generous showers in central and northern Punjab with till mid of August, with most parts of country are covered by the monsoon precipitation. In 2011, contrarily to the normal pattern, the location of monsoon depression remained southwest in India and a high pressure system was developed over the Bay of Bengal that moved in the southwest direction, instead of its usual northwestern route, thereby entering Pakistan from Rajasthan to Sindh. As discussed earlier, a high pressure system is characterized as having light winds and air subsidence. The Tibetan high (generally located above 30°N during monsoon) restricts the incursion of monsoon winds, and the monsoon activities normally take place below its ridge. However, in 2011, the Tibetan high moved unusually downward at about 26 °N due to which the air moisture could not traveled in the upper parts of country and was therefore restricted only to the lower parts. Secondly, the intense surface heating in Balochistan during the summer season results in seasonal LPS over the area with the normal pressure of about 1000 hpa prevails in the province during the season. However, on 9th August, the air pressure was 4 hpa less than its normal value due to the exceptionally high air temperatures recorded over the province, thereby pulling excess moisture from the monsoon system present at the eastern boundary of Sindh. On 10th August, the trough formed over the arid plains in Sindh facilitated the incursion of excess moisture from the Arabian Sea and resulted in monsoon extreme precipitation [50]. As per PMD, during the first two weeks of September, about 760 mm of rainfall was received in Mithi, 603 mm in Mirpur Khas, 353 mm in Nawabshah, 348 mm in Dadu, 268 mm in Dadu, 244 mm in Hyderabad, and 212 mm was received in Karachi (*PMD Annual Climate Report, 2011*).

In 2012, due to the unusual heating of the Indian Ocean, a depression was formed over the Bay of Bengal in the last week of August that moved towards Sindh and resulted in extreme monsoon precipitation over the province. As per PMD, during the intense rainfall spell from 5th to 11th September, 481 mm was received in Jacobabad, 216 mm in Larkana, 206 mm in Sukkur, and 205 mm in Rohri (*PMD Annual Climate Report, 2012*). In 2013, normal to slightly above normal monsoon precipitation was received in Pakistan as a whole, except the Sindh province (21% below normal). In July, 31% below normal rainfall was received in Pakistan, with the highest withdrawal in Sindh (-84%), followed by Balochistan (-57%), KPK (-11%), Punjab (-9%), and Azad Jammu & Kashmir (-7%). However, in August, Pakistan as a whole received 59% above average rainfall, with Balochistan (+144%), Gilgit-Baltistan (+108%), Sindh (+50%), KPK (+40%), and Azad Jammu & Kashmir (+24%). In September, the monsoon system was weak, and the country received 24% less rainfall than usual (*PMD Annual Climate Report, 2013*).

In 2014, unusual drought conditions prevailed during the first two months of monsoon in Pakistan, where in July, Pakistan received 39% below normal rainfall, with the highest deficit was found in Sindh (-97%), followed by Balochistan (-42%), and Azad Jammu & Kashmir (-24%). Similarly, in August, the drought conditions sustained, and the country received 49% below normal rainfall. However, in September, due to the unusual heating over the northern areas, a trough was formed over Kashmir, which then moved eastward towards the northern Pakistan. This depression played a key role in pulling the moisture from Indian Ocean towards the northern areas, that resulted in torrential rainfalls over Azad Kashmir (+181%), Gilgit-Baltistan (+531%), and Punjab (+225%), while below average rainfall was observed in Sindh (-12%) and Balochistan (-12%). As per PMD, during the four-day rainfall spell from 1st to 5th September, 557 mm of rainfall was received in Lahore, 523 mm in Sialkot, 345 mm in Rawalpindi, 345 mm in Mangla, 298 mm in Islamabad, 228 mm in Faisalabad, and 220 mm of rainfall was received in Jhelum (*PMD Annual Climate Report, 2014*).

In 2015, Pakistan as a whole received 27% above normal monsoon rainfall, with the highest departure was observed in Gilgit-Baltistan (+116%). In July, Pakistan as a whole received 40% above normal rainfall, with Gilgit-Baltistan (+95%), KPK (+19%), Punjab (+69%), and Sindh (+78%), while a deficit (-22%) was observed in Balochistan. Contrarily, in August, Pakistan received 8% below normal rainfall, with the highest withdrawal was found in Sindh (-96%), followed by Balochistan (-62%), and Azad Jammu and Kashmir (-37%), while Punjab and KPK received 20 % and 54 % above normal rainfall respectively. In September, Pakistan as a whole received 41% above average rainfall, with the highest departure in Gilgit-Baltistan (+316%), followed by Punjab (+71%), Sindh (+29%), and Azad Jammu & Kashmir (+28%), while below normal rainfall was observed in Balochistan (-30%) (*PMD Annual Climate Report, 2015*). In 2016, Pakistan as a whole received 25% above normal monsoon rainfall, with the highest departure was observed in Punjab (+55%). In July, Pakistan received slightly less than normal rainfall (-14%), with the highest withdrawal was found in Balochistan (-41%), followed by Azad Jammu and Kashmir (-15%). However, in August, 76% above normal rainfall was received in Pakistan, with the highest departure in Sindh (+149%), followed by Punjab (+107%), KPK (+56%), Gilgit-Baltistan (+23%), and Balochistan (+6%). In September, slightly above normal rainfall was received in Pakistan as a whole (+7%), with Gilgit-Baltistan (+44%), KPK (+32.4%), Punjab (+39%), while in Sindh, 92% below normal rainfall was received (*PMD Annual Climate Report, 2016*). In 2017, drought conditions prevailed during the monsoon, where Pakistan as a whole received 22% below normal rainfall. In July, Pakistan received 20% below normal rainfall, except Sindh, where close to normal rainfall was received. In August and September, the similar pattern was sustained, and the country received 28% and 19% below normal rainfall respectively (*PMD Annual Climate Report, 2017*). In 2018, similar drought conditions were noticed during monsoon, where Pakistan as a whole recorded 31% below normal rainfall, with the highest deficit was observed in Sindh and Balochistan. In July, Pakistan as a whole received 12% below average rainfall, while provincially, above normal rainfall was received in Punjab, KPK, and Gilgit-Baltistan. In August and September, the similar pattern prevailed, and the country received 51% and 35% below average rainfall respectively (*PMD Annual Climate Report, 2018*).

In 2019, Pakistan as a whole received near to normal monsoon rainfall, with the above normal monsoon precipitation was mainly focused on the Sindh province (+46%). In July, Pakistan as a whole received 8% below normal rainfall, with the highest deficit was observed in Gilgit-Baltistan (-59%), followed by Azad Jammu & Kashmir (-24%), Balochistan (-19%), KPK (-11%), and Punjab (-9%), while Sindh received 24% above normal rainfall. In August, 52% above average rainfall was received in Sindh and 35% above normal in Gilgit-Baltistan, while the remaining parts of country recorded below normal rainfall. In September, Pakistan as a whole received 15% above normal rainfall, with Sindh (+99%), Balochistan (+48%), and Punjab (+28%), while a negative departure was found in Gilgit-Baltistan (-75%), KPK (-49%), and Azad Jammu & Kashmir (-23%) (*PMD Annual Climate Report, 2019*). In 2020, Pakistan received 41% above normal monsoon rainfall, making it the 4th wettest year since 1960, with the extreme precipitation was mainly centered in Sindh and Balochistan during the early monsoon. Apart from precipitation, the temperature patterns were also extreme during the year. In 2020, Pakistan recorded 0.22 °C higher mean annual temperature than normal. In August, the country observed 0.76 °C above normal temperature, with Sindh observed 1.1 to 2.2 °C, and Balochistan observed 0.1 to 1.9 °C above normal temperature. Similarly, in September, Pakistan recorded 0.29 °C above normal temperature, with Sindh observed 0.8 to 2.3 °C, and Balochistan observed 0.7 to 1.9 °C above average temperatures. These unusual high temperatures resulted in intense depression over the arid plains of Sindh and Balochistan, thereby maintaining an active intrusion of moisture from the Indian Ocean, which resulted in extreme precipitation over the country. In July, Pakistan as a whole received 34% below normal rainfall. However, in August, the monsoon gained strength, and the country as a whole received 108% above normal rainfall, with Sindh (+363%), Balochistan (+271%), Punjab (+14%), KPK (+9%), and Gilgit-Baltistan (+20%). In September, the rainy season shifted northwards, with the highest departure was observed in Punjab (+139%), followed by KPK (+120%), Gilgit-Baltistan (+113%), Sindh (+87%), Azad Jammu & Kashmir (+24%), while a significant deficit was noted in Balochistan (-96%) (*PMD Annual Climate Report, 2020*).

In 2021, the intrusion of monsoon system in Pakistan was delayed by 5 days from its usual date (30th June), with 19% above average monsoon rainfall was received in Gilgit-Baltistan, while Pakistan as a whole received 9% below normal rainfall. In July, Pakistan received 4% above normal rainfall, with the highest departure in Gilgit-Baltistan (+86%), followed by KPK (+28%), and Balochistan (+22%), while a significant deficit was observed in Sindh (-47%). In August, Pakistan as a whole received 89% below normal rainfall, with the highest deficit was observed in Sindh (-89%), followed by Punjab (-67%), Azad Jammu & Kashmir (-63%), Balochistan (-54%), and KPK (-39%). Contrarily, in September, Pakistan as a whole received 60% above normal rainfall, with the highest departure in Sindh (+234%), followed by Balochistan (+64%), Punjab (+44%), and Azad Jammu & Kashmir (+18%), while below normal rainfall was observed in Gilgit-Baltistan (-19%) and KPK (-1%) (*PMD Annual Climate Report, 2021*).

In 2022, Pakistan witnessed one of the worst floods in its history due to the exceptionally high monsoon rainfall, and the expeditious melting of glaciers and snow mass over its northern areas due to the unusual high temperatures. On the annual scale, Pakistan observed 0.84 °C above normal temperature, with the mean maximum temperature was 0.95 °C, and the mean minimum temperature was 1.29 °C above normal. Spatially, the mean annual temperature anomaly was highest over KPK (+1.14 °C), followed by Azad Jammu and Kashmir (1.04 °C), and Gilgit-Baltistan (+0.14 °C). As per PMD, 16 Glacier Lake Outburst Flood (GLOF) events took place in KPK and Gilgit-Baltistan in 2022, as compared to the usual 5 to 6 GLOF events every year. Due to the warm temperatures and intense tough over the plains, rainfall amount and intensity also deviated significantly from its normal pattern. In 2022, Pakistan received 175% above normal monsoon precipitation, with the rainy system was most intense in Balochistan (+450%) and Sindh (+426%), as shown in the Figure 2. In July, Pakistan as a whole received 181% above normal rainfall with the highest departure in Balochistan (+450%), followed by Sindh (+307%), Punjab (+116%), KPK (+30%), and Gilgit-Baltistan (+32%), as shown in the Figure 3. In August, the situation was more severe with 243% above average rainfall was received in the country. Spatially, the departure was highest in Sindh (+726%), followed by Balochistan (+590%), Gilgit-Baltistan (+233%), KPK (+58%) and Punjab (+52%), as shown in the Figure 4. During the heavy rainfall spell from 1st July to 26th August, the Padidan station in Sindh received the record high 1764 mm of rainfall due to the consistent trough over Sindh. In September, due to the beginning of monsoon retreating from the country, Pakistan received 21% below normal rainfall, with the highest deficit in Balochistan (-59%), followed by Punjab (-21%), Gilgit-Baltistan (-19%), and KPK (-16%) as shown in the Figure 5 (*PMD Annual Climate Report, 2022*).

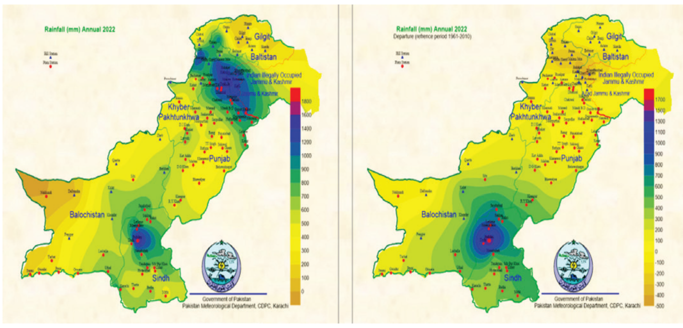

Figure 2: Pakistan Spatial Distribution of 2022 Annual Precipitation and Departure from Normal

Source: PMD Annual Climate Report, 2022

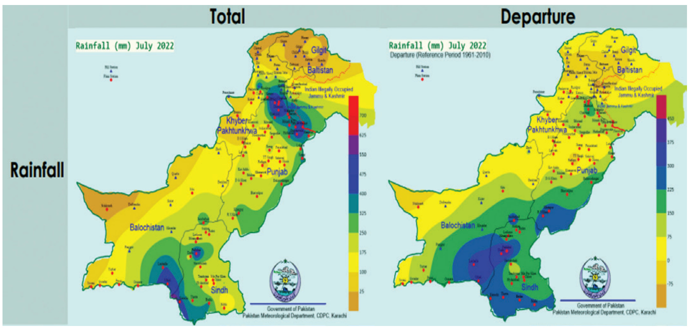

Figure 3: Pakistan Spatial Distribution of July 2022 Precipitation and Departure from Normal

Source: PMD Annual Climate Report, 2022

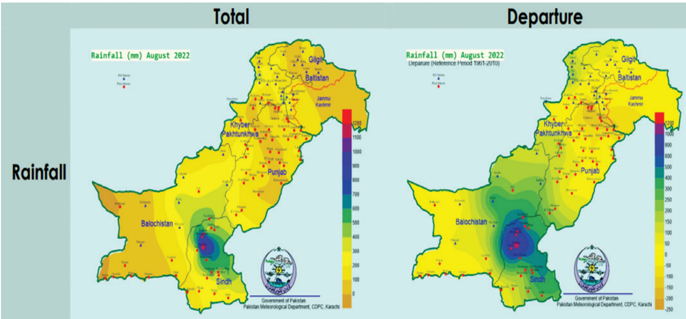

Figure 4: Pakistan Spatial Distribution of August 2022 Precipitation and Departure from Normal

Source: PMD Annual Climate Report, 2022

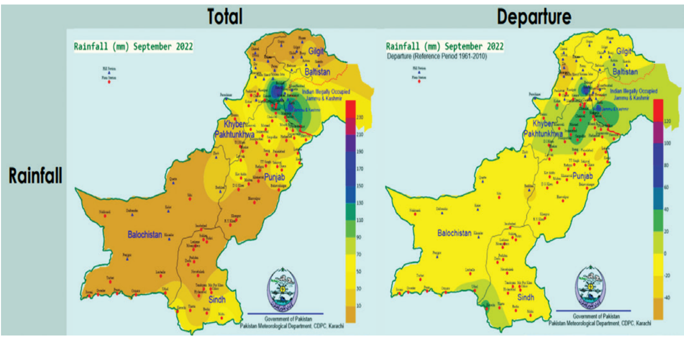

Figure 5: Pakistan Spatial Distribution of September 2022 Precipitation and Departure from Normal

Source: PMD Annual Climate Report, 2022

The above literature review clearly showed that the extremity in monsoon precipitation in Pakistan is gaining momentum as a consequence of the changing climate patterns, which necessitates to investigate the major atmospheric factors behind the occurrence of severe storm events in the country. Therefore, this study was conducted to probe the major meteorological causes behind the extreme monsoon precipitation in Pakistan in 2022. The methodology adopted to achieve the study outcomes is shown in the Figure 6. The outcomes of this study are expected to deeply understand the major factors that played a key role in the occurrence of extreme monsoon precipitation in 2022, and to devise an effective climate change adaptation and mitigation strategy for the country.

2.0 DATA AND METHODOLOGY

2.1 Study Area

Pakistan spatially lies in the Temperate zone and partially in the Sub-Tropics, between the latitudes 23 to 35 °N and between the longitudes 60 to77 °E with a total area of about 796,096 km^2, with the political map of country shown in the Figure 7. Geographically, Pakistan is divided into three main zones including the northern highlands, the Indus river plain, and the Balochistan plateau [51]. The northern highlands consist of the Hindukush, Karakoram, and the Pamir mountain ranges. The Balochistan plateau is located in the west and the vast Thar Desert in the eastern part of country. The 1609 km length of Indus River and its tributaries flow through the country from Kashmir to the Arabian Sea, with an expanse of alluvial plains along the river basin in Punjab and Sindh [52].

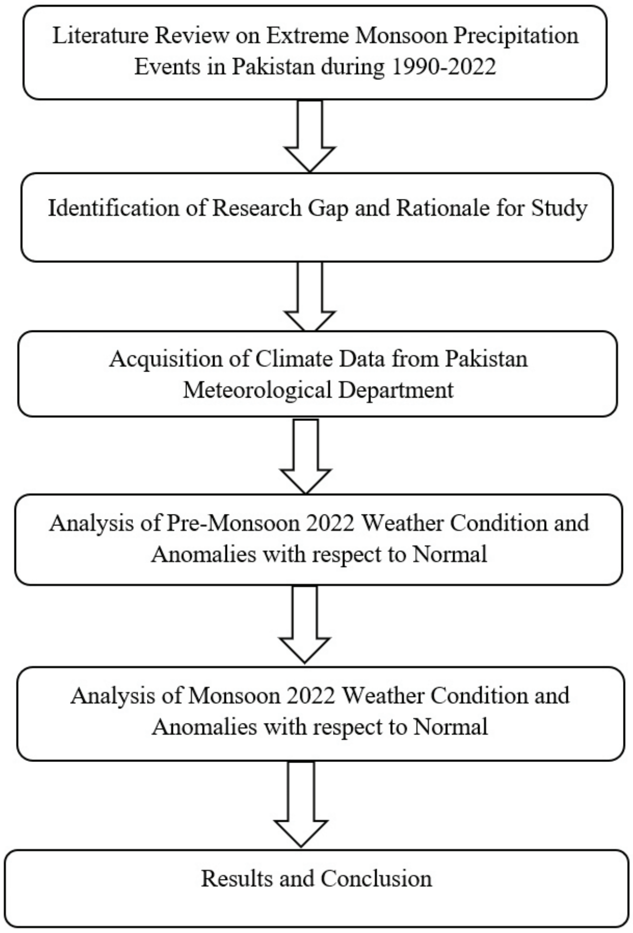

Figure 6: Flow Chart Describing the Methodology Adopted to Achieve the Study Objectives

Climatologically, Pakistan has a continental type of climate with high climate variations over the year. The mean annual precipitation of Pakistan is about 300 mm, with 141 mm comes from the southwest summer monsoon, and 74 mm from the winter precipitation. Seasonally, the weather patterns vary as cool, dry winter from December to February, a hot spring from March to May, followed by a rainy summer season due to the intrusion of southwest monsoon moist winds into the country, and the retreating monsoon period from October to November. Depending on the location and season, Pakistan receives all three kinds of precipitation including the convective, frontal, and orographic precipitation [53]. During the pre-monsoon period, localized convective rainfall is received occasionally which normally contributes about 12% to the annual total rainfall of country. During summer, Pakistan receives the major share of its annual precipitation from the southwest monsoon during July to September. The post-monsoon period in the country is relatively dry, and acts as a transition period between the summer and winter season. The scarce rainfall in autumn contributes about 4% to the annual precipitation of Pakistan. During the winter season, Pakistan receives generous snowfall over the northern and northwestern highlands, and liquid precipitation over the northern and central Punjab, KPK, and Kashmir [47]. In this study, a number of 25 climate stations across Pakistan lying in the southwest monsoon zone were selected (as shown in Figure 8). The geographical and climate details of the selected stations are shown in the Table 2.

Figure 7: Political Map of Pakistan

Source: Survey of Pakistan

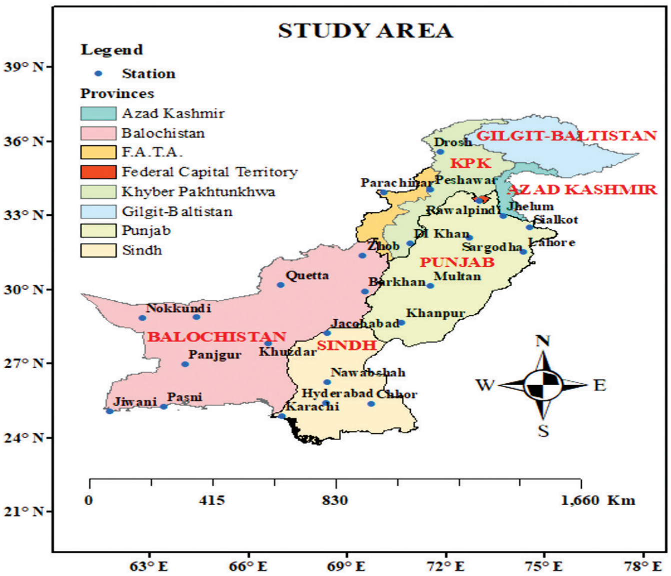

Figure 8: Description of Study Area Showing the Selected Climate Stations

The climate data required for the study was acquired from PMD for the period 1990-2022. The acquired data consisted of monthly maximum and minimum air temperature (°C), air pressure and vapor pressure at station level (mb), and rainfall (mm), along with the monthly climate normal for the period 1961-2010 for all selected stations.

2.2 Methodology

2.2.1 Analysis of Pre-Monsoon 2022 Weather Condition and Anomalies

As discussed earlier, the pre-monsoon weather conditions in Pakistan strongly influence the monsoon precipitation characteristics in the country. Therefore, in this study, in order to investigate the prime atmospheric factors that lead to the extreme monsoon precipitation in Pakistan in 2022, the monthly air temperature and pressure data for the pre-monsoon months (April to June) for the year 2022 was comprehensively analyzed, and the magnitude of anomaly with respect to normal (1961-2010) was computed for all stations, so as to understand the extent of variation from the normal pattern that resulted in the unusual weather conditions in the country.

Table 2: Geographic and Climate Details of the Selected Stations

Source: Pakistan Meteorological Department (PMD)

Station	Latitude (°N)	Longitude (°E)	Mean Annual Temperature (°C)	Mean Annual Precipitation (mm)
Khyber Pakhtunkhwa				
Drosh	35.56	71.8	17.60	588
Peshawar	34.01	71.52	22.70	404
Parachinar	33.90	70.08	15.30	782
DI Khan	31.86	70.90	24.20	318
Punjab				
Rawalpindi	33.56	73.01	21.30	1200
Sargodha	32.07	72.68	24.70	501
Jhelum	32.94	73.72	23	875
Sialkot	32.49	74.52	22.6	972
Lahore	31.52	74.35	24.30	636
Multan	30.15	71.52	25.65	254
Khanpur	28.63	70.65	25.10	97.3
Balochistan				
Zhob	31.34	69.46	19.10	285
Quetta	30.17	66.97	15.70	261
Barkhan	29.89	69.52	21.60	418.6
Nokkundi	28.82	62.75	24.50	35.30
Dalbandin	28.88	64.39	22.40	80.70
Panjgur	26.97	64.08	22.10	109
Khuzdar	27.81	66.60	21.50	252
Jiwani	25.05	61.77	25.60	114
Pasni	25.25	63.41	26.28	115
Sindh				
Jacobabad	28.24	68.38	27.10	223
Nawabshah	26.24	68.39	26.70	161
Hyderabad	25.39	68.35	26.80	156
Chhor	25.35	69.73	26.50	245.50
Karachi	24.86	67	26.60	175

2.2.2 Analysis of Summer Monsoon 2022 Weather Condition and Anomalies

In this study, after the comprehensive analysis of unusual pre-monsoon weather conditions, the monthly precipitation and vapor pressure data for the monsoon months (July to September) for the year 2022 was analyzed for all stations, and the magnitude of anomaly with respect to normal was estimated.

3.0 RESULTS AND DISCUSSION

3.1 Analysis of Pre-Monsoon 2022 Weather Condition and Anomalies:

The results obtained from the pre-monsoon air temperature and pressure analysis for the year 2022 are shown in the Figures 9 to 14 as under:

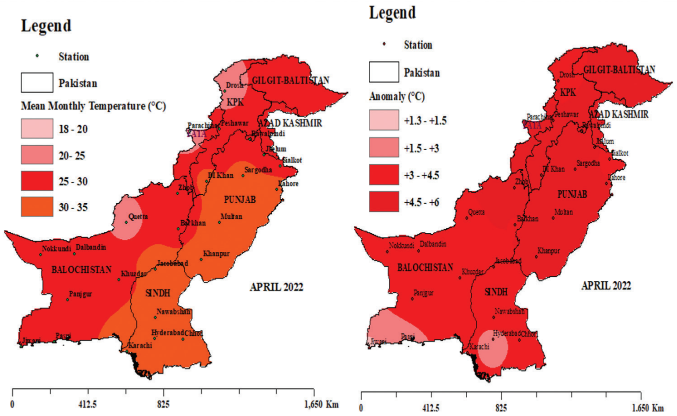

Figure 9: Mean Monthly Temperature (°C) in April 2022 (on left) and the Magnitude of Anomaly (°C) (on right)

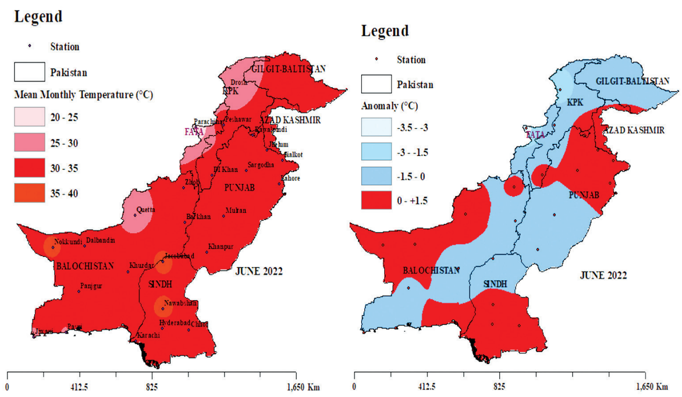

Figure 11: Mean Monthly Air Temperature (°C) in June 2022 (on left) and the Magnitude of Anomaly (°C) (on right)

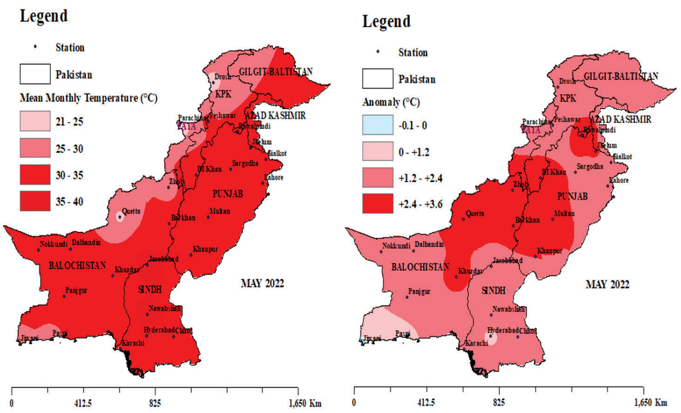

Figure 10: Mean Monthly Air Temperature (°C) in May 2022 (on left) and the Magnitude of Anomaly (°C) (on right)

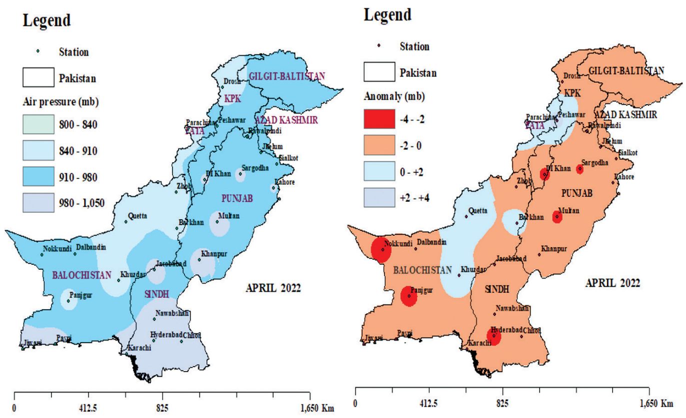

Figure 12: Mean Monthly Air Pressure (mb) in April 2022 (on left) and the Magnitude of Anomaly (mb) (on right)

Table 3: Summary of Mean Monthly Temperature Analysis and Anomalies in °C for the Pre-Monsoon Period 2020-2022, Sindh

				2022					
Station	**April**	**Normal**	**Anomaly**	**May**	**Normal**	**Anomal**	**June**	**Normal**	**Anomaly**
Karachi	31.5	28.5	+3	32.4	30.8	+1.6	32.2	31.7	+0.5
Chhor	32.9	29.9	+3	34.5	33.2	+1.3	34.1	33.6	+0.5
Hyderabad	33.2	31	+2.2	34.4	33.4	+1.0	34.2	34.1	+0.1
Nawabshah	33.7	29.5	+4.2	36.3	34.1	+2.2	35.9	35.6	+0.3
Jacobabad	34.1	30.2	+3.9	37.3	35.2	+2.1	36.1	37	-0.9
				2021					
Karachi	30.9	28.5	+2.4	32.6	30.8	+1.8	32.2	31.7	+1.1
Chhor	32.2	29.9	+2.3	34.2	33.2	+1.0	33.9	33.6	+0.6
Hyderabad	31.6	31	+0.6	33.3	33.4	-0.1	33	34.1	-0.3
Nawabshah	31.7	29.5	+2.2	34.6	34.1	+0.5	35.1	35.6	-0.3
Jacobabad	31	30.2	+0.8	35.7	35.2	+0.5	36.6	37	-0.4
				2020					
Karachi	28	28.5	-0.5	31	30.8	+0.2	31.9	31.7	+0.2
Chhor	31.3	29.9	+1.4	33.4	33.2	+0.2	33.9	33.6	+0.3
Hyderabad	31.2	31	+0.2	33.9	33.4	+0.5	33.9	34.1	-0.2
Nawabshah	29.9	29.5	+0.4	34.5	34.1	+0.4	36	35.6	+0.4
Jacobabad	30.8	30.2	+0.6	35.9	35.2	+0.7	37.9	37	+0.9

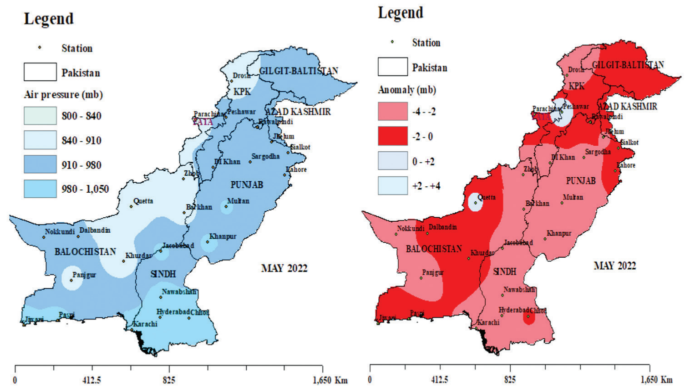

Figure 13: Mean Monthly Air Pressure (mb) in May 2022 (on left) and the Magnitude of Anomaly (mb) (on right)

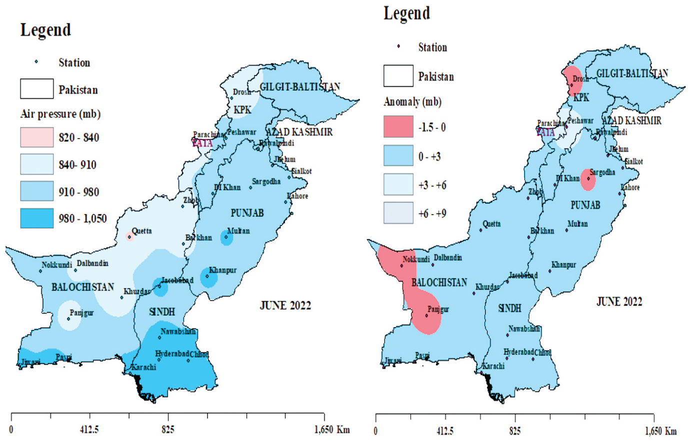

Figure 14: Mean Monthly Air Pressure (mb) in June 2022 (on left) and the Magnitude of Anomaly (mb) (on right)

The results obtained from the analysis showed that the pre-monsoon temperatures were exceptionally high across the country in 2022. As mentioned earlier, the pre-monsoon heating over the landmasses in Pakistan plays a vital role in the formation of seasonal trough that sets an adequate ground for the incursion of moisture-laden winds from the Arabian Sea and Bay of Bengal into the country. In this study, the pre-monsoon air temperature analysis showed that the magnitude of temperature anomaly was highest in Balochistan throughout the pre-monsoon season. In April 2022, Balochistan recorded about 1.2 to 6.0 °C above normal monthly temperature as shown in the Figure 9, with the magnitude of anomaly was found to be highest at the Zhob station (+5.9 °C), followed by Panjgur (+4.4 °C), Khuzdar (+4.3 °C), Nokkundi (+4.1 °C), Dalbandin (+3.4 °C), and Pasni (+1.6 °C). In Sindh, about 2.0 to 4.5 °C above normal temperature was found, with Nawabshah (+4.2 °C), Jacobabad (+3.9 °C), Karachi (+3 °C), and Hyderabad and Chhor (+2.2 °C) as shown in the Table 3. In Punjab, about 4.0 to 5.8 °C above normal temperature was found with the highest anomaly at the Rawalpindi station (+5.8 °C), followed by Sargodha (+5.4 °C), Multan (+4.6 °C), Jhelum (+4.5 °C), and Sialkot (+4.1 °C). In KPK, about 3.5 to 5.5 °C above normal temperature was found, with the maximum anomaly in Dera Ismail Khan (+5.5 °C), followed by Peshawar (+4.6 °C), Parachinar (+4.4 °C), and Drosh (+3.7 °C). In May, the monthly temperature anomaly was found to be +1.0 to +3.5 °C in Balochistan as shown in the Figure 10, with the highest anomaly detected in Zhob (+3.2 °C), followed by Barkhan (+2.7 °C), Khuzdar (+2.5 °C), Dalbandin (+2.3 °C), and Panjgur (+1.9 °C). In Sindh, about 1.0 to 2.5 °C above normal temperature was noticed, with Nawabshah (+2.2 °C), Jacobabad (+2.1 °C), and Karachi (+1.6 °C). In Punjab, about 1.2 to 3 °C above normal temperature was found, with Rawalpindi (+2.9 °C), Multan (+2.5 °C), Sargodha (+2.4 °C), and Lahore (+1.8 °C). Similarly, in KPK, about 1.0 to 3 °C above normal temperature was found during the analysis, with the highest anomaly in Dera Ismail Khan (+3 °C). In June, 0.1 to 0.5 °C above normal temperature was found in Sindh, 0.2 to 1.2 °C in Punjab, while below normal temperature was observed at majority of stations in KPK and Balochistan, as shown in the Figure 11.

Due to the profound relation between the air temperature and pressure, the pre-monsoon air pressure conditions in 2022 also deviated from its normal pattern due to the unusual high air temperatures. In this study, the analysis revealed that in April 2022, majority of the stations in Sindh, Punjab, and Balochistan observed significant below normal mean monthly air pressure, with the air pressure anomaly ranging from about -0.5 to -2.5 mb (millibar) in Balochistan, -1.0 to -2.5 mb in Sindh, and about -1.5 to -2.2 mb in Punjab, as shown in the Figure 12. Similarly, in May, Sindh recorded about 2.0 to 3.0 mb below normal air pressure, and Balochistan and Punjab observed 1.0 to 3.0 mb below average air pressure, as shown in the Figure 13. However, in June, majority of the selected stations showed a positive anomaly as shown in the Figure 14.

Based on the above analysis, it was concluded that the unusual pre-monsoon heating during April and May over the plains in Sindh, Punjab and Balochistan played a key role in the development of intense low air pressure system, that paved the way for the excess moisture intrusion from the Arabian sea and Bay of Bengal into the country. This excess moisture penetration consequently lead to high air moisture conditions, and ultimately extreme precipitation in Pakistan.

3.2 Analysis of Monsoon 2022 Weather Condition and Anomalies:

In this study, after the investigation of unusual pre-monsoon weather conditions in Pakistan in 2022, the monsoon seasonal air moisture conditions (evaluated in terms of vapor pressure) and rainfall were investigated for the year 2022. The results obtained from the analysis are shown in the Figures 15 to 20 as under:

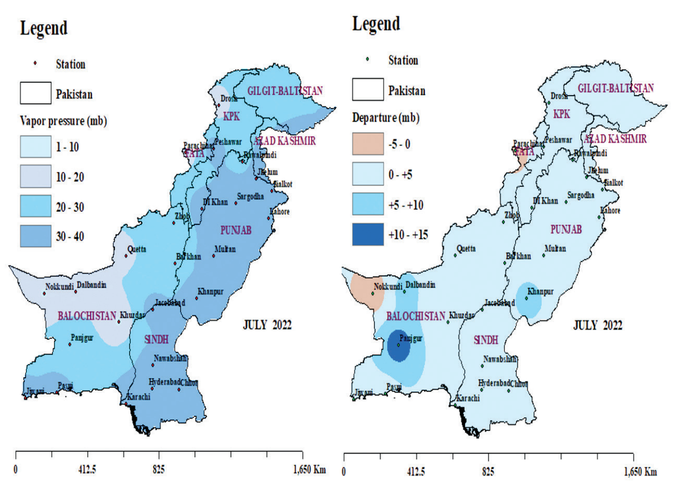

Figure 15: Mean Monthly Vapor Pressure (mb) in July 2022 (on left) and the Magnitude of Anomaly (mb) (on right)

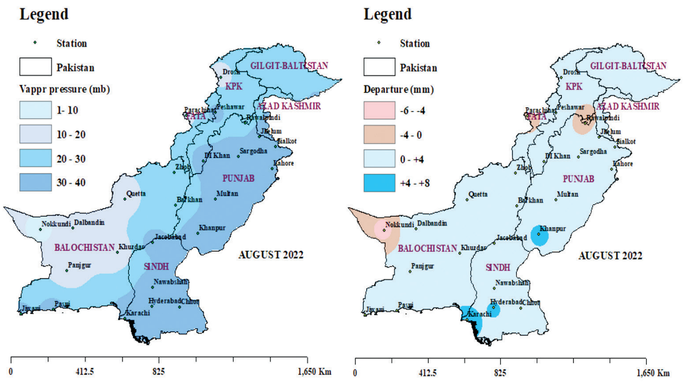

Figure 16: Mean Monthly Vapor Pressure (mb) in August 2022 (on left) and the Magnitude of Anomaly (mb) (on right)

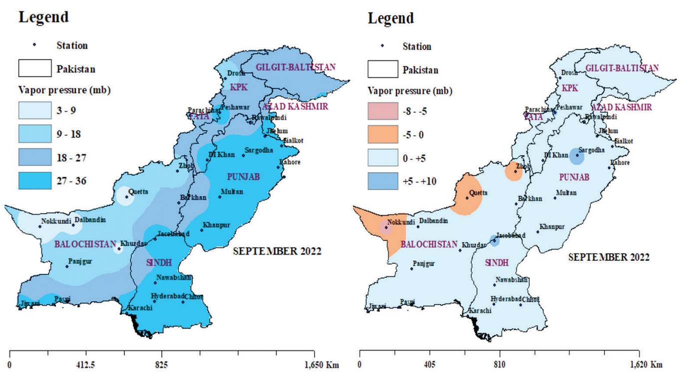

Figure 17: Mean Monthly Vapor Pressure (mb) in September 2022 (on left) and the Magnitude of Anomaly (mb) (on right)

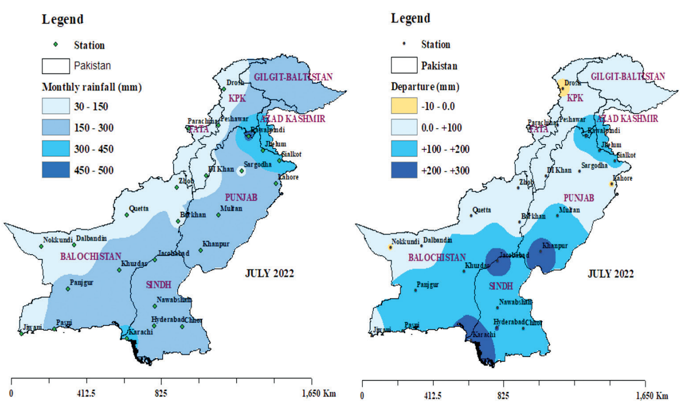

Figure 18: Monthly Rainfall (mm) in July 2022 (on left) and the Magnitude of Departure (mm) (on right)

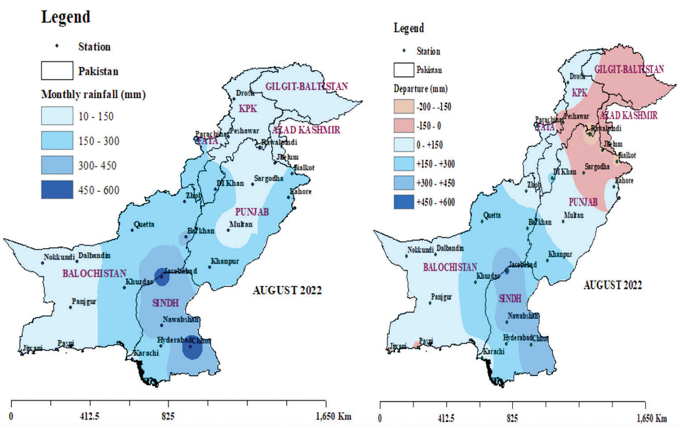

Figure 19: Monthly Rainfall (mm) in August 2022 (on left) and the Magnitude of Departure (mm) (on right)

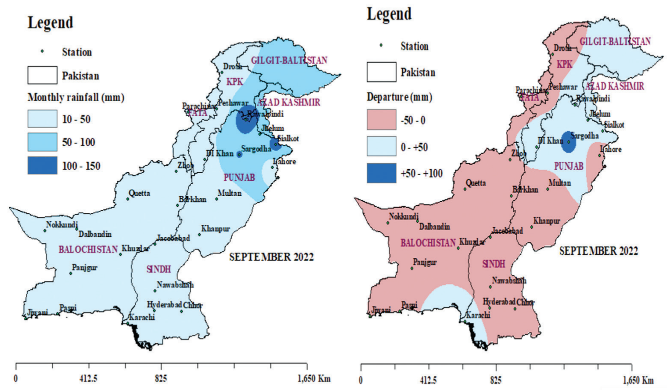

Figure 20: Monthly Rainfall (mm) in September 2022 (on left) and the Magnitude of Departure (mm) (on right)

As discussed earlier, vapor pressure generally indicates the availability of water vapors in air and strongly governs the intensity and the amount of precipitation. In this study, the analysis showed that in July 2022, about 0.4 to 4.0 mb above normal mean monthly vapor pressure was observed in Balochistan, 0.2 to 4.0 mb in Sindh, and 1.0 to 5.0 mb in Punjab and KPK, as shown in the Figure 15. In August, the analysis showed about 1.0 to 4.0 mb above normal mean monthly vapor pressure in Balochistan, and 1.5 to 5.0 mb in Sindh and Punjab, as shown in the Figure 16. In September, about 3.0 to 6.0 mb above normal vapor pressure was found in Sindh and Balochistan during the analysis, as shown in the Figure 17. As discussed earlier, the availability of high amount of water vapors in air serve as a key cause of heavy precipitation. In this study, the rainfall analysis revealed that the extreme monsoon system was more active in Sindh and Balochistan, as compared to the other parts of country in 2022. In July 2022, Sindh received about 100 to 300 mm above normal monthly rainfall as shown in the Figure 18, where Karachi and Jacobabad stations received 282 and 247 mm above normal precipitation respectively. In Balochistan, about 50 to 200 mm above normal rainfall was received, with 177 mm above normal rainfall in Khuzdar, followed by Panjgur (+165 mm), Pasni (+162 mm), and Zhob (+78 mm). Similarly, in Punjab, about 50 to 180 mm above normal rainfall was received, with 176 mm above normal rainfall in Rawalpindi, followed by Jhelum (+120.5 mm), and Sialkot (+119 mm). In KPK, about 5 to 30 mm above normal rainfall was received, where Peshawar received 22 mm above average rainfall. In August, precipitation over the country was found to be more vigorous than July during the analysis, where Sindh received about 100 to 500 mm above normal rainfall (as shown in the Figure 19), with the highest departure was found in Jacobabad (+457 mm), followed by Chhor (+435 mm), Nawabshah (+402 mm), Hyderabad (+180 mm), and Karachi (+67 mm). In Balochistan, about 50 to 250 mm above average rainfall was received, with 224 mm above normal rainfall in Barkhan, followed by Quetta (+194 mm), Khuzdar (+170 mm), Zhob (+111 mm), and Panjgur (+62 mm). However, in Punjab, all selected stations received below normal rainfall. In KPK, 161 mm above normal rainfall was received in Dera Ismail Khan, followed by Drosh (+122 mm), and Parachinar (+68 mm). In September, the intense monsoon system was found to be retreated from the country with less extremity in rainfall as compared to July and August. In Sindh, Karachi recorded 33 mm above normal rainfall, while the remaining stations received below average precipitation. In Punjab, about 15 to 75 mm above normal rainfall was received, with 75 mm above normal rainfall in Sargodha, followed by Rawalpindi (+28 mm), and Sialkot (+20 mm), as shown in the Figure 20.

Based on the above analysis, it was concluded that the unusual heating and the formation of intense low air pressure condition during April to May over Sindh, Punjab, and Balochistan resulted in the excess penetration of moisture from the Arabian sea and Bay of Bengal, that lead to air moisture levels, and consequently extreme precipitation in the country. The series of heavy monsoon rainfall events severely affected the human lives, livestock and agriculture, and infrastructure in Pakistan. As per the Pakistan Agricultural Research Council (PARC), about 1.9 million tons of rice, 3.1 million bales of cotton, and 10.5 million tons of sugarcane worth of $543, 485, and 273 million respectively was destroyed in Sindh as a consequence of extreme monsoon precipitation.

4.0 SIGNIFICANCE AND RESEARCH CONTRIBUTION

This study comprehensively highlighted the causes and extremity of extreme monsoon precipitation in Pakistan during the past 30 years. In addition, it also unearthed the occurrence of unusual weather conditions that lead to the exceptionally high monsoon precipitation in 2022. The outcomes of study are expected to provide a way forward for the national and international research community in investigating the causes and impacts of extreme weather patterns, and to suggest effective climate change adaptation and mitigation measures.

5.0 RESEARCH SCOPE AND LIMITATIONS

This study included an in-depth literature review on the past extreme monsoon rainfall events in Pakistan, and also probed the meteorological factors behind the extreme monsoon rainfall in 2022. Additionally, to devise a more holistic and effective climate change adaptation and mitigation strategy, the Global or the Regional Climate Models can also be employed to capture the future possible trend and extremity of southwest monsoon in the region.

6.0 CONCLUSION AND RECOMMENDATIONS

This study was conducted to probe the major meteorological causes behind the extreme monsoon precipitation in Pakistan in 2022. Based on the analysis, the following conclusions were reached:

- The detailed literature review on the past monsoon precipitation pattern in Pakistan revealed that the extreme monsoon rainfall events have significantly increased in the country as a consequence of shifting climate patterns.
- The temperature analysis revealed that in April 2022, unusual high air temperatures were recorded across the country, with Sindh observed 2.0 to 4.5 °C, Balochistan observed 1.5 to 6.0 °C, Punjab observed 4 to 5.8 °C, and KPK observed 3.5 to 5.5 °C above normal temperature. Similarly, in May, about 1.0 to 2.5 °C above normal temperature was found in Sindh, 1.0 to 3.5 °C in Balochistan, Punjab, and KPK.
- Due to the exceptionally high air temperature, an intense low pressure system was developed over the country's landmasses. In April 2022, about 0.5 to 2.5 mb below normal air pressure was observed in Sindh and Balochistan, and 1.5 to 2.5 mb in Punjab. In May, 2.0 to 3.0 mb below normal air pressure was found in Sindh and 1.0 to 3.0 mb in Balochistan and Punjab.
- In July 2022, about 0.5 to 4.0 mb above normal vapor pressure was found in Sindh and Balochistan, while Punjab observed 1.0 to 5.0 mb above normal vapor pressure. In August, about 1.5 to 5.0 mb above normal vapor pressure was found in Sindh, Punjab, and Balochistan, while in September, about 3.0 to 6.0 mb above normal vapor pressure was found in Sindh and Balochistan during the analysis.
- Due to the high moisture availability, about 100 to 300 mm above normal monthly rainfall was received in Sindh in July, with 50 to 200 mm in Balochistan and Punjab, and about 30 mm in KPK. In August 2022, about 100 to 500 mm above normal rainfall was received in Sindh, and 50 to 250 mm in Balochistan. In Punjab, majority of the stations received below normal rainfall, while in KPK, about 50 to 180 mm above average rainfall was received. In September, the monsoon system weakened in the country, with Sindh, Balochistan, and KPK received below average rainfall, while Punjab received 15 to 75 mm above normal rainfall.
- Conclusively, it was found that the unusual heating during April to May in Sindh, Punjab, and Balochistan resulted in the formation of intense trough that facilitated the continuous moisture penetration from the Bay of Bengal and Arabian sea into the country. This uninterrupted incursion of water vapors lead to increased vapor pressures (high air moisture conditions) and consequently extreme precipitation in the country.
- The study outcomes briefly explained the causes of extreme monsoon precipitation in Pakistan in 2022, which may help to devise an effective climate change adaptation and mitigation strategy, so as to reduce the risks of extreme climate patterns on the water and food security in Pakistan.
- In the authors opinion, in order to reduce the risk and consequences of severe hydrological and climate events (floods, extreme rainfall and heat waves) in Pakistan, a continuous real time monitoring of hydro-climatological patterns, along with the implementation of a well-integrated climate change mitigation policy is essential so as to ensure the state of water, food, and economic security in the country.

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