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Climate Change and its Impacts across Pakistan

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Abstract Climate change and variability is best manifested by persistent global temperature rise, changing precipitation patterns, increasing frequency of extreme weather events, rapidly shrinking ice sheets & glacier melting and sea-level rise. This study analyzed the rainfall (for three major seasons; monsoon, winter & spring), temperature (in three indices; annual mean, annual daytime and annual nighttime temperatures) and extreme events recorded at 56 data sites across Pakistan over 63-years period (1961-2023) to investigate the climate change and diagnose the trends. We did time-series analysis to assess the annual variability and applied the Mann-Kendall statistical trend test to determine the trend's significance. Results showed a significant rise in annual-average temperature, annual maximum as well as annual minimum temperatures all over Pakistan and at 27 stations individually, annual maximum temperature at 28 and annual minimum at 25 stations across Pakistan. In rainfall, the annual and spring (AMJ) rains have shown significant rising trend throughout Pakistan, while, the summer monsoon (JAS) rainfall showed a statistically significant increase at 8 stations in the north with decrease at 2 sites in southwest, winter (DJFM) rainfall witnessed an increase at 3 sites and so was the spring (AMJ) at 7 sites mostly in the south, while a decrease at 3 sites in north of the country (all changes being significant at 95- 99% CI). Extreme events include an increase in annual high-temperature extreme (T_{max} > 35 °C), decrease in annual cool nights (T_{min} < 10 °C) and increase in wet days. The snowfall has decreased in both amount and frequency of snow days in KP, GB and Punjab hilly station, Murree. There is an increasing frequency of cyclone formation in the Arabian Sea, particularly the intensity being significant. Sea-level data analysis depicted a 2.02 mm/year sea-level rise at Karachi coast. Increased cyclones frequency coupled with potentially heightened storm surges and sea-level rise may prove fatal to coastal areas.

Keywords; Climate change, extreme weather events, rainfall, temperature, sea-level rise, tropical cyclone.

Introduction

The climate change and variability is best exhibited by persistent global temperature rise, changing precipitation patterns, increasing frequency of extreme events, fast shrinking ice sheets & glacier melting and sea-level rise. With increasing greenhouse gases (GHGs) and anthropogenic activities, there has been a steep rise in global annual average temperature. The year 2023 has been the warmest ever year in last 100,000 years with annual average temperature being 1.45°C above pre-industrial levels (Forster et al. 2024; Ripple et al. 2023; Perkins-Kirkpatrick et al. 2024; WMO-No. 1347; Copernicus Climate Change Services, Global Climate Highlights 2023). Each of the last four decades has been continually warmer than the preceding one since 1850 (IPCC, 2021). The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) determined that the global surface temperature was 0.99°C higher than 1850-1900 (preindustrial era) during 2001-2020 which rose even higher to 1.09°C during 2011–2020 with bigger upsurges being terrestrial than the oceanic (IPCC, 2021).

The report further determines that frequent and intense climate and weather extreme events (heavy precipitation, drought and wildfire) have implications for ecologies, people, and infrastructure. Progressively since the Assessment Report (AR5), these experiential influences are linked with climate change caused by human activities, particularly through amplified occurrence of dangerous events. Increasing human death toll, warm-water coral blenching and demise, and enlarged wildfires pointedly ascribed to human-caused climate alteration in some areas. Antagonistic effects from tropical cyclones, with associated losses and reparations, have amplified due to sea level increase and the surge in heavy rainfall. Human induced climate change has bearings in natural and social systems from slow-onset processes such as oceanic acidification, sea level rise or regional declines in rain (IPCC, 2021).

South Asia is susceptible to a variety of hydromet hazards with Pakistan, Bangladesh and Nepal falling in the top 10 vulnerable countries to climate change (Germanwatch, 2021). Numerous studies have observed the climate-induced influence on agronomy segment round the world (Lobell & Burke, 2008; Pirttioja et al., 2015; Bannayan et al., 2011; Gachence et al., 2015; Asseng et al., 2011; Rosenzweig et al., 2014).

Pakistan, principally an agriculture country, has been evolving a prone country to climate variation impacts. Temperature and precipitation pointedly influence the seasonal crops of the country. Pakistan existing in barren to semi-dry area and depending mainly on irrigated farming is confronting the hostile consequence of climate alteration with glaciers withdrawal, prolonged rain deficits, reducing of winters and early onset of summers (CIMMYT, 1989; Aslam et al., 2004; Rasul et al., 2011; Anon. 2013; Anon. 2007). The changing climate impacts are evident in Pakistan because of its dependence on ecological and natural conditions, sharp population evolution rate and concentration, small capability to minimize the adverse impacts of climate change (Sarfaraz et al. 2021).

Socio-economic impacts of climate change-induced extreme weather events

The World Meteorological Organization (WMO) reports that worldwide reported economic losses by natural hazards (Drought, Extreme temperatures, Flood, Landslides, Storm and Wildfire) have increased from US$183.9 billion over 1970-1979 to US$1476.2 billion over 2010-2019 (Newman and Noy, 2023; WMO, 2021B). Newman and Noy (2023) find that extreme weather events cost US$ 143 billion annually and that is attributable to climatic change with 63% being due to human loss of life. Between 1990 and 2022, 1,210 meteorological, hydrological, climatological disasters were reported in the South Asia, cumulatively affecting over 1.8 billion persons in nine south Asian countries and leading to over 420 thousand deaths. The economic damages from the disasters are estimated to be close to US$ 250 billion (EM-DAT, 2022). The altering climate might abruptly lessen existing situations for up to 800 million people in a region where world's deprived and most susceptible inhabitants live. Importantly, climate alteration related losses in GDP (grand domestic production) per capita are projected to be higher than the global average by up to seven percent (WB, 2021). Pakistan faced an unprecedented and most devastating floods of its history in the year 2022, which induced mainly by climate change (WWA, 2022) inflicted an unparalleled loss and damage to the country with 33 million people affected including 8 million displaced, 1700 death toll and one million livestock perished. This disaster alone caused damage of US$14.9 billion to infrastructure and US$15.3 billion loss to national economy. The worst affected sectors were housing (US$5.6 billion); agriculture, food, livestock, and fisheries (US$3.7 billion), transport and communications (US$3.3 billion) (NDMA, 2022). Previously, a similar devastating flood of 2010 also affected more than 18 million people, ruthlessly smashed the infrastructure, and caused nearly 2000 mortalities with estimated damages of US$10 billion, of which 50 percent were losses in the agriculture sector (ADB and World Bank, 2010; USAID, 2010; Houze et al., 2011; Webster et al., 2011). In 2011, in the southern province of Sindh, anomalous precipitation again led to extensive flooding that resulted in over 400 fatalities and affected more than 8 million people. Again, in 2012, southern Pakistan received uncharacteristic rainfall and flooding, which resulted in over 450 fatalities and affected over 5 million people. During 1998-2001, another extreme event, the protracted drought took heavy toll on crop and livestock production in the country when about 2.2 million people and 7.2 million heads of livestock were affected, and 143 humans and 2.5 million livestock were perished due to severe drought conditions in 1999-2000 (Barlow et al. 2002; Sarwar, 2008). Moreover, that worst drought resulted in rapid downfall in economic growth from 6 percent to mere 2.6 percent coupled with 60 to 80 percent crops failure (Sarwar, 2008). Another extreme weather event is the heatwave, which incidentally is increasing in frequency and severity with rising global temperatures (IPCC, 2021). Karachi, the metropolitan city of Pakistan faced one of the most decimating such phenomenon in 2015 when 1350 people died and other 50000 suffered heat-related illness (Anwar et al. 2022; Hanif, 2017; Commissioner-Karachi, 2017; Chaudhry et al. 2015). Pakistan coastal shelf stretching over about 1050 km too remains under constant threat from tropical cyclones (TC) developing in the Arabian Sea. In recent years three TCs directly struck the Pakistan coast. TC *02A* (May 1999) which struck the Thatta district, Sindh, caused about US$6 million worth damages and 700 human lives, TC *Yemyin* (June 2007) stricking the Ormara-Pasni area inflicted $560 million damages with 950 casualties and TC *Phet* (June 2010) took toll of 44 human lives accompanied with $780 million worth damages across Oman, Pakistan and some parts of India (Sarfaraz and Dube, 2012). The June 2023 TC, *Biparjoy*, proved to the longest lasting cyclone (13 days, 6-17 June) in the history of the Arabian Sea due only to constant prevalance of favourable environmental conditions, owing to climate change-induced increased sea surface temperatures (SSTs) (PMD, 2023).

The changing climate, therefore poses a serious risk to biodiversity, water availability, food safety, social justice and general security. Changing weather and climate patterns primarily affect the water availability for irrigation. For instance, in 1987 the faint monsoonal rains caused drastic reduction in crops production in Bangladesh, India, and Pakistan, compelling Pakistan and India to import wheat (WFI, 1988). Several countries from the tropical and sub-tropical regions are possibly more susceptible to warming due to additional increase in temperature that will disrupt water balance and damage agronomic sector (Santer et al., 1996; Mendelssohn et al., 2000; McCarthy et al., 2001; Obioha, 2008). The change in climate intensifies the vulnerability of agronomic regions to storms, drenching rain and scarcities, which may fetch imminent threat of socio-economic damages. Several studies have demonstrated the climate impacts for specific crops and areas in Pakistan (Shakoor et al. 2011; Amir & Nazareth 2011; Siddiqui et al. 2012; Janjua et al. 2011; Ashfaq et al. 2011). Several native and peripheral harvests have already been destroyed due to insistent climate change and variability that caused a marked anxiety amongst the small farmers. Key yields are exceedingly dependent on temperature and precipitation patterns (Sarfaraz et al. 2021).

Area of Study

This research work covers the entire Pakistan stretching between Latitude 24.0 °N to 36.0 °N and Longitude 61.5 °E to 76.5 °E with India situated to its east, Afghanistan and Iran in the west, China in the north and the Arabian

Sea in south (Fig. 1). Pakistan has a distinctive and diverse land: bordered by the Himalayan, the Karakoram and the Hindu Kush mountain ranges in the north/ northwest to Southeast. These mountains; K-2 (8611m, 2nd in the world), Nanga Parbat (8126m, 8th) and Gasherbrum-I (8068m, 11th in the world), play a crucial part in regulating the inbound weather patterns in Pakistan. There are three vast deserts, Thar located in Sindh, Cholistan and Thal in Punjab and highland deserts in southwest Balochistan. The country's longest river Indus and its streams provide main source of irrigation of two provinces, Punjab and Sindh. Agriculture sharing the 21.4% in GDP, 45% of labour power is a main source of income of 67% inhabitants of the country (M/o NFS&R, 2013-14). Cotton, wheat, rice, sugarcane, lentils and grams are the main crops with mangos, oranges, banana, apricots and apples grown abundantly in several parts across the country.

The overall harvested area is about 22.14 million hectares (mha) with 79.6mha (88%) is arid to semi-arid and 50.88mha (63.9%) being foraging. The Northern-Pakistan ecosystem is also semi-arid but moist. Sindh province is largely dry while Punjab and Balochistan are scorched/semi-scorched with 58:29 and 43:57 ratios respectively. By ecologies, 51.5% extent is dry, 36.9% is semi-dry, 5.4% is sub-humid, and 6.2% is mixed. Virtually 41mha is completely unfertile and 11mha consists of deserts where hyper-arid is the common climate (Adnan et al. 2017).

With this backdrop, this study by analyzing the real-time meteorological data recorded at 56 data sites investigated how far the climate of Pakistan has actually changed over the period of 63 years (1961-2023), what implications could be with persistent climate change and suggest what are the adaptation and mitigation measures.

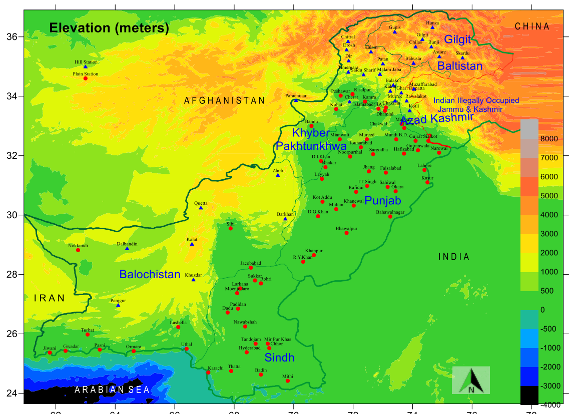


Fig. 1. Location of meteorological stations network used in the study.

Materials and Methods

Climate data consisting of daily and monthly rainfall, temperature (Mean, Minimum and Maximum) recorded at 56 meteorological stations, snowy days and tropical cyclone (formation frequency and intensity) over the North Arabian Sea for 63 years period (1961 to 2023) were obtained from the Pakistan Meteorological Department (PMD). This is a quality-controlled data, which PMD uses in its monthly and annual reports and *Climatic Normals'* publications. The selected 56 stations include 25 hilly stations (with elevation in excess of 800 meters) and 31 plain stations (elevation less than 800 meters) with three of them located along the coast. The stations (altitude range of 2-2209 meters) used are well distributed across the Pakistan landscape (Fig. 1).

We categorized the "wet days" (or extreme rain) when the 24-hour rainfall exceeded the 30 mm, "hot days" are defined where the maximum (daytime) temperature exceed 35 °C, "cool nights" are when the minimum (nighttime) temperature happen to be below 10 °C (Kysely, 2010; Tjaša, 2018). From the given dataset, we determined the "*wet days*", "*hot days*" and "*cool nights*" to find out their trends over 63-year period because the extreme weather events are on rise locally as well as globally (IPCC, 2021). Pakistan encompasses mainly three rainy seasons; the monsoon (July-September, JAS, winter (December-March, DJFM and spring (April-June, AMJ). Therefore, this study analysed the rainfall for the three seasons, temperature (annual mean, annual daytime and annual nighttime) to investigate the climate variability and diagnose the trends.

Precipitation and temperature long-term trends are determined by using a non-parametric statistical test proposed by Mann-Kendall (MK) (Mann, 1945; Kendall, 1975; Gilbert, 1987). Working on distribution-free assumption the MK test provides a statistical valuation of ascendant/ descendant variable over a definite time. An arising (declining) trend specifies if there is a persistent surge (weakening) in the variable value over the period; the preference may or may not be straight. Hirsch et al. (1982) described this test as the best investigative exploration tool and as such is more fitting to determine situations where deviations are significant or of abundant range. Rainfall distribution is usually not smooth and continuous, hence a non-parametric test (like MK test) application proves more appropriate over irregular and discontinuous sample distribution. MK test statistics are given below;

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

and

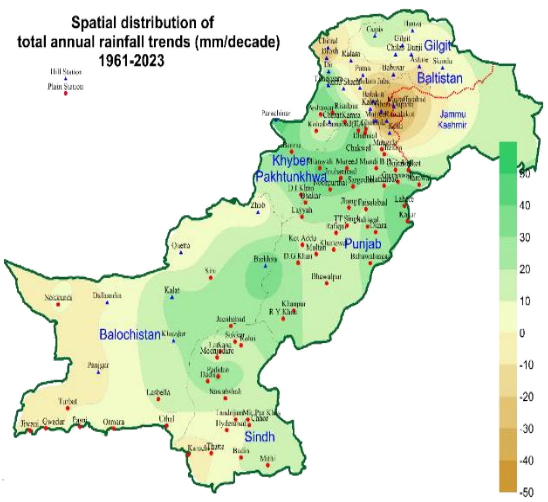
$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0. \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases}$$

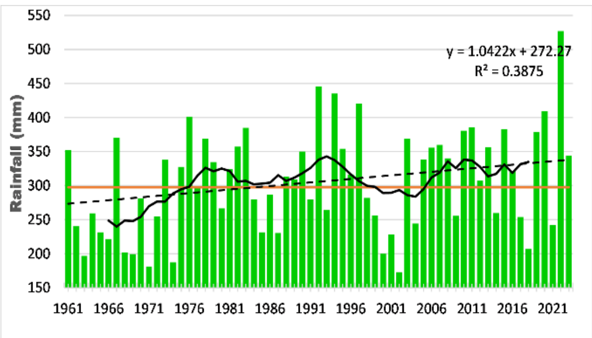
Where 'Xj' and 'Xk' represent the time series observations in chronological order with 'n' being the time series length. Positive 'Z' indicates an upward trend and negative means downward trend in the rainfall or temperature time series (Pohlert, 2016).

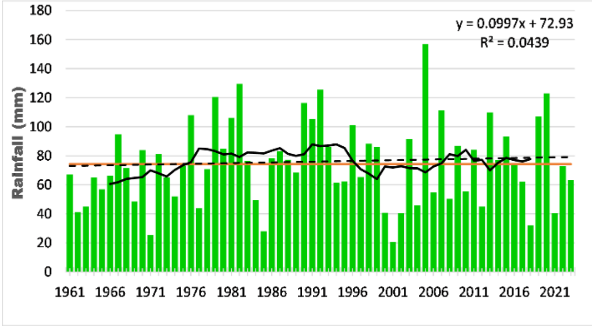
Results and Discussion

Rainfall change analysis

The two climatic parameters, rainfall and temperature, are crucial to determining the climate of an area (Köppen 1936). To assess how far these climate parameters have undergone a change, we analysed them in annual and seasonal rainfall indices and *wet days* for extreme rainfall, daytime maximum temperatures for *hot days* and nighttime (minimum) temperatures for *cool nights* and the results are as follows. Figure 2a demonstrates the spatial distribution of annual rainfall linear trends over the country from 1961 to 2023 that indicates a statistically significant increasing trend across most parts of Pakistan. The increasing trends are evident over Khyber Pakhtunkhwa (KP) and plain areas of Punjab, while, a declining trend in southwest Sindh, Azad Jammu & Kashmir (AJ&K), northern KP and sub-mountain Punjab. A significant increase of 11 mm/decade over 63- year period for Pakistan with 3-maxima and 3-minima (Fig. 2b). Seasonal rains also depict a distinct spatial as well as temporal variability with long-term winter (Dec-Mar, DJFM) and monsoon (Jul-Sep) rains too exhibits an interannual variability but statistically insignificant (Fig. 2c & 2d respectively). Whereas, the third major seasonal rain (April-June, spring or pre-monsoon) shows a statistically significant increasing trend.







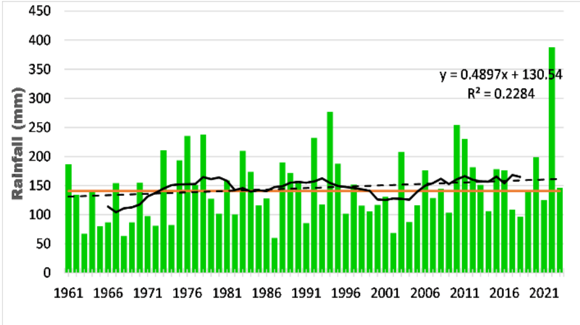
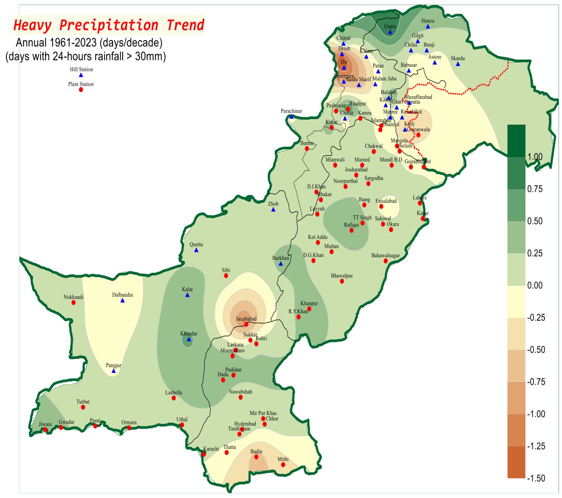


Fig. 2 Rainfall trends in Pakistan over 63-year period: (a) annual rain spatial distribution, (b) yearly rainfall time series with linear trend, (c) same as 'b' but for winter (Dec-Mar) and (d) same as 'b' but for monsoon, Jul-Sep (JAS). Black line indicates the 11-years moving average with 11-years averaged value positioned at the middle year of each 11-years slab. The red straight line shows the annual long-term average (1961-1990) and the black dotted line shows the trend over the period.

Analysis of heavy rain events and snow-days

Apart from temperature, precipitation is another most vital weather parameter that contributes to the climate of an area and to study its variability, change and extremes in changing climate is so crucial for different sectors like, environment, agriculture, health, power and ecology. Precipitation, if too much leads to flood and when too little leads to drought. Globally, the incidence of heavy/extreme precipitation is on the rise over some places primarily due to unabated increasing global warming which causes more water to evaporate (estimated 7% more evaporation with each 1°C rise, IPsC 2021). This study analysed the rainfall for *extreme* or *wet* days (>30 mm/24-hour) which indicated an increase of 0.25 to 1.0 days/decade across most parts the country except small pockets in southern Sindh, southwest Balochistan, northwest KP, extreme north Punjab and AJ&K where a decline is distinctively visible (Fig. 3a).

Winter snowfall is a crucial contributor to overall precipitation aggregate of the country. It is the snowfall and perennial ice over high mountains, Himalaya, Karakorum & Hindukush (HKH) that drives the rivers flow in following spring/summer season, which subsequently runs lifeline of irrigation, hydroelectric power generation and domestic water use. Therefore, analysis of snowfall has been carried out which revealed that number of snow days has decreased by 6-8 days at snow-receiving stations; Astore, Chitral, Drosh, Murree, Parachinar and Skardu over last 63 years (Fig. 3b).



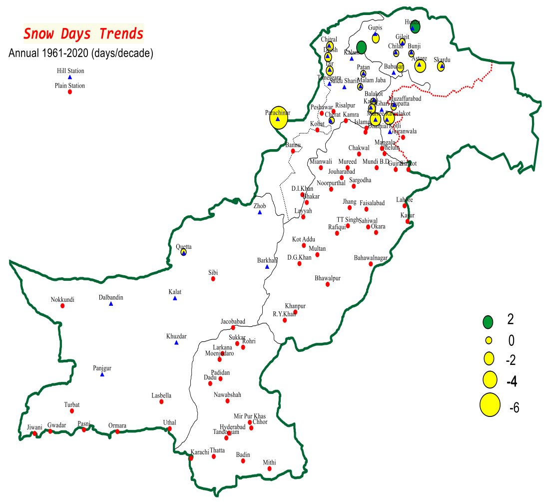


Fig. 3 (a) Spatial distribution of heavy precipitation (24-hour rain > 30mm) trends during 1961–2023 and (b) Trends in annual average snow days in 1961–2020 (days/decade).

The seasonal rainfall analysis at 56 stations individually showed a statistically substantial upsurge in JAS-rain at eight locations in the north and decrease at two sites in southwest of the country. So was the trend of winter (DJFM) and spring (AMJ) rainfall at three and seven sites (mostly in the south) respectively, while a decrease at three sites in north of the country (all changes being significant at 95- 99% CI) (Table 1).

Table 1. Seasonal rainfalls trends (with S & Z statistics, p-values) using Mann-Kendall test.

No	Station	S Statistic	Z value	p-value	Test Result
	a. Monsoon (JAS) rainfall trend				
1	Bunji	355	2.57	0.01**	Statistically significant increasing trend
2	Chilas	448	3.2453	0.001**	Do
3	Gupis	271	1.9601	0.04*	Do
4	Skardu	421	3.0494	0.002**	Do
5	Islamabad	332	2.403	0.02*	Do
6	Risalpur	315	2.2795	0.02*	Do
7	Peshawar	319	2.3087	0.02*	Do
8	Mianwali	453	3.2813	0.001**	Do
9	Dalbandin	-249	2.0134	0.04*	Statistically significant decreasing trend
10	Garhi-dupatta	-397	2.8784	0.004**	Do
11	Jiwani	-255	2.0632	0.04*	Do
	b. Winter (DJFM) rainfall trend				
1	Dir	301	2.1779	0.03*	Statistically significant increasing trend
2	Kalat	291	2.1057	0.04*	Do
3	Mianwali	287	2.1338	0.03*	Do
	c. Spring (AMJ) rainfall trend				
1	Barkhan	454	3.2888	0.001**	Do
2	Bhawalnagar	463	3.3541	0.0008**	Do
3	Bahawalpur	276	1.9973	0.05*	Do
4	Khuzdar	278	2.0109	0.04*	Do
5	Lahore	284	2.0545	0.04*	Do
6	Lasbella	458	3.3207	0.0008**	Do
7	Mianwali	348	2.5191	0.01**	Do
8	Chitral	-335	2.4247	0.02*	Statistically significant decreasing trend
9	Drosh	-380	2.7514	0.006**	Do
10	Garhi-dupatta	-407	2.9474	0.003**	Do

** Significant at 99% confidence interval and * significant at 95% confidence interval.

Temperature change analysis

The spatial distribution of mean annual temperature changes across Pakistan during 63 years period is shown in Fig. 3a. An ample evidence of warming is distinctly noticeable across almost entire country except an isolated cool bias in extreme north-northwest of the country with warming being more pronounced over Balochistan, most of Sindh, and eastern parts of Punjab. Analysis of annual mean temperature anomalies indicates a warming of 0.186 °C/decade with a continuous positive anomaly since 1998. A similar rising trend is also evident in daytime (maximum) and nighttime (minimum) temperature analysis (Figs. 4c, d). The analysis of annual mean, annual maximum (daytime) and annual minimum (nighttime) temperatures showed a statistically significant rise in all three temperature indices across Pakistan. The same analysis at each of 56 stations revealed a significant rising trend in annual mean temperature at 27 stations, annual maximum temperature at 28 and annual minimum at 25 stations across Pakistan (Table 2).

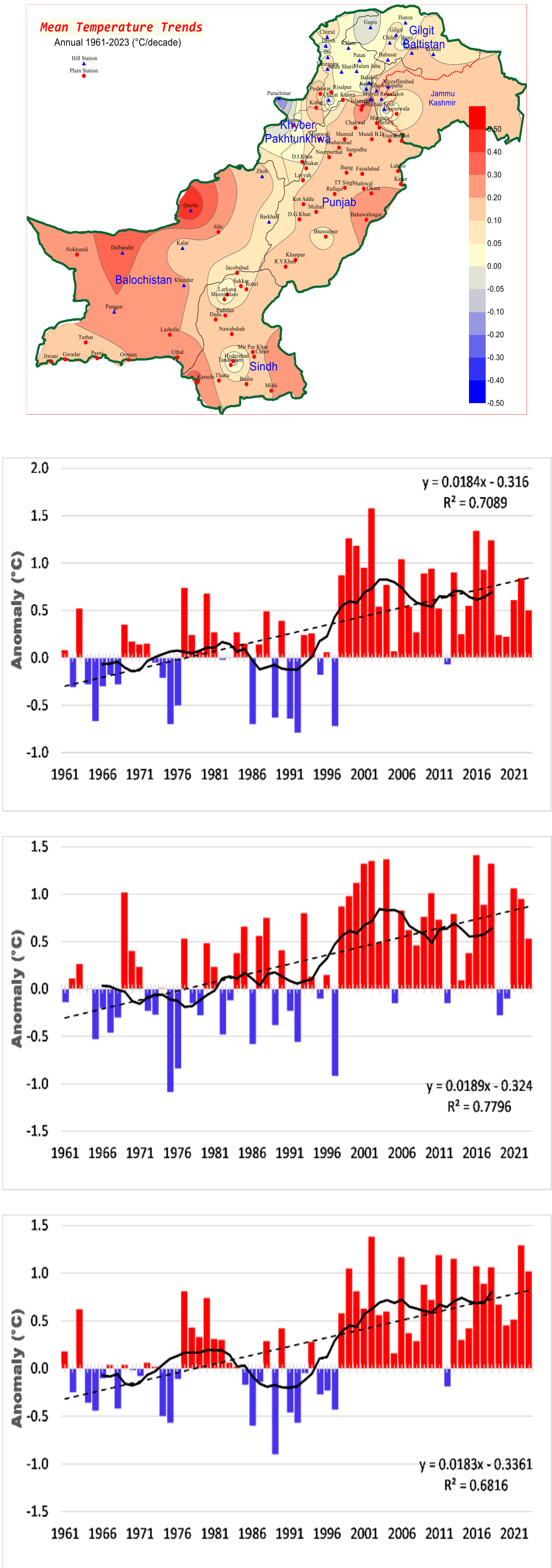


Fig. 4 (a) Spatial distribution of annual mean temperature trend across Pakistan, (b) Annual mean temperature anomalies for 1961-2023, (c) Same as 'b' but for annual maximum temperature, (d) Same as 'c' but for annual minimum temperature. Black line indicates 11-years moving average with 11-years averaged value put at the middle year of each 11-years slab. Black dotted line shows the trend over the period 1961-2023. Anomalies are computed with 1961-1990 base period.

Table 2. Annual Mean, Maximum and Minimum Temperatures trends of Pakistan and individual stations using Mann-Kendall trend test.

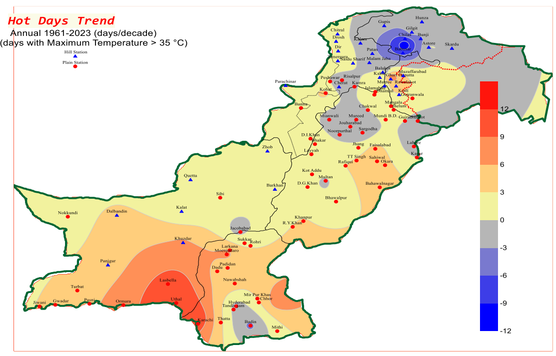
No	Station	S statistic	Z value	p-value	Test result
			a. Annual Mean Temperature Trend		
	Pakistan	709	4.2115	2.5371E-05**	Significantly increasing trend
1	Chhor	436	3.6479	0.0003**	Do
2	Dalbandin	582	3.6479	1.0621E-06**	Do
3	Karachi	728	6.097	1.0809E-09**	Do
4	Lasbella	350	2.9317	0.003**	Do
5	Nawabshah	406	3.3993	0.0007**	Do
6	Nokkundi	541	4.5251	6.0381E-06**	Do
7	Padidan	588	4.941	7.7731E-07**	Do
8	Panjgur	509	4.2579	2.0636E-05**	Do
9	Quetta	752	6.2909	3.1565E-10**	Do
10	Astor	285	2.3836	0.02*	Do
11	Bhawalnagar	490	4.1005	4.1223E-05**	Do
12	Faisalabad	346	2.8962	0.004**	Do
13	Garhi-Dupatta	396	3.3131	0.0009**	Do
14	Gilgit	275	2.299	0.02*	Do
15	Islamabad	503	4.2087	4.1223E-05**	Do
16	Jehlum	346	2.8985	0.004**	Do
17	Khanpur	272	2.2724	0.03*	Do
18	Kohat	319	2.6661	0.007**	Do
19	Lahore	608	5.0923	3.5379E-07**	Do
20	Multan	367	3.0711	0.002**	Do
21	Murree	384	3.2106	0.002**	Do
22	Peshawar	408	3.4135	0.0006**	Do
23	Sargodha	567	4.7451	2.0836E-06**	Do
24	Skardu	248	2.0718	0.04*	Do
25	Khuzdar	266	2.4349	0.02*	Do
26	Moenjo-Daro	255	3.779	0.0002**	Do
27	Rafiqui	270	2.9254	0.004**	Do
28	Parachinar	-334	2.7915	0.005**	Significantly decreasing trend
29	Bunji	-314	2.6234	0.008**	Do
30	Cherat	-298	2.4885	0.02*	Do
			b. Annual Maximum Temperature Trend		
	Pakistan	635	3.7681	0.00016447**	Significantly increasing trend
1	Astor	322	2.6898	0.007**	Do
2	Chhor	584	4.8922	9.9716E-07**	Do
3	Chitral	464	3.8793	0.0001**	Do
4	Dalbandin	615	5.1442	2.6868E-07**	Do
5	Dir	357	3.2717	0.001**	Do
6	Drosh	272	2.2707	0.03*	Do

7	Faisalabad	243	2.03	0.04*	Do
8	Garhi-Dupatta	580	4.8508	1.2298E-06**	Do
9	Gilgit	464	3.8802	0.0001**	Do
10	Gupis	304	2.5381	0.01**	Do
11	Islamabad	368	3.0765	0.002**	Do
12	Jiwani	518	4.3402	1.4235E-05**	Do
13	Karachi	641	5.3761	7.6105E-08**	Do
14	Khuzdar	286	2.6189	0.008**	Do
15	Kohat	505	4.2222	2.4193E-05**	Do
16	Murree	556	4.647	3.368E-06**	Do
17	Muzaffarabad	267	2.2287	0.03*	Do
18	Nawabshah	461	3.8583	0.0001**	Do
19	Nokkundi	455	3.8036	0.0001**	Do
20	Ormara	340	2.8916	0.004**	Do
21	Panjgur	364	3.0413	0.003**	Do
22	Pasni	408	3.4153	0.0006**	Do
23	Peshawar	321	2.6825	0.007**	Do
24	Quetta	490	4.0976	4.1739E-05**	Do
25	Risalpur	252	2.1045	0.04*	Do
26	Saidu-Sharif	11	1.9844	0.04*	Do
27	Skardu	558	4.6687	3.0318E-06**	Do
28	Zhob	455	3.8044	0.0002**	Do
29	Cherat	-335	2.7992	0.005**	Significantly decreasing trend
30	Kalat	-710	5.9371	2.9006E-09**	Do
	c. Annual Minimum Temperature Trend				
	Pakistan	766	4.5483	5.41E-06**	Significantly increasing trend
1	Badin	574	4.8098	1.5112E-06**	Do
2	Bhawalnagar	664	5.5579	2.7303E-08**	Do
3	Dalbandin	466	3.8983	9.6886E-05**	Do
4	Chilas	241	2.0154	0.04*	Do
5	Faisalabad	307	2.5699	0.01**	Do
6	Hyderabad	241	2.0184	0.04*	Do
7	Islamabad	614	5.1379	2.7781E-07**	Do
8	Jacobabad	368	3.0844	0.002**	Do
9	Jehlum	632	5.2937	1.1984E-07**	Do
10	Karachi	602	5.0419	4.6083E-07**	Do
11	Khanpur	390	3.2616	0.001**	Do
12	Khuzdar	223	2.04	0.04*	Do
13	Lahore	838	7.0121	2.3476E-12**	Do
14	Mianwali	313	2.6183	0.008**	Do
15	Moenjo-daro	338	4.8022	1.5692E-06**	Do
16	Multan	608	5.0889	3.6008E-07**	Do
17	Nokkundi	441	3.6878	0.0002**	Do
18	Padidan	330	2.7623	0.005**	Do
19	Panjgur	564	4.7195	2.3643E-06**	Do
20	Peshawar	339	2.8381	0.005**	Do
21	Quetta	832	6.9854	3.441E-12**	Do
22	Rafiqui	378	4.0978	4.1705E-05**	Do
23	Sargodha	684	5.7214	1.0564E-08**	Do
24	Sialkot	266	2.2232	0.03*	Do
25	Sibbi	284	2.3788	0.02*	Do
26	Bunji	-367	3.0648	0.002**	Significantly decreasing trend
27	Chitral	-374	3.1302	0.002**	Do
28	Gilgit	-299	2.5008	0.01**	Do
29	Gupis	-430	3.5965	0.0003**	Do
30	Kakul	-500	4.1807	2.9055E-05**	Do
31	Kotli	-351	2.937	0.003**	Do
32	Ormara	-264	2.305	0.01**	Do
33	Parachinar	-395	3.3005	0.0009**	Do
34	Skardu	-293	2.4544	0.02*	Do

'E' – exponential, ** Significant at 99% confidence interval and * significant at 95% confidence interval.

Trend analysis hot days and cold nights

Given the global temperature is rising continuously and unabatedly leading to more frequent heatwaves around the globe, we analysed the temperature for *hot days* (maximum temperature =>35°C) and *cold nights* (minimum temperature <10°C) over the period 1961–2023. The result reveals that annually there is an increase of 3-9 days across most areas of the country except GB, northwest Punjab, parts of KP and isolated places in southern Sindh and northeast Balochistan where a decrease of 3 days is evident (Fig. 5a). The *cold nights* have decreased by 3-12 nights across Sindh, Balochistan (except isolated place in northeast) and Punjab, whilst, a 3-6 nights increase across much of GB, northwest KP and isolated northeast Balochistan is evident (Fig. 5b). An increase in hot days indicates a possible upsurge in future heatwaves and decreasing cold nights indicate shrinking winter season.



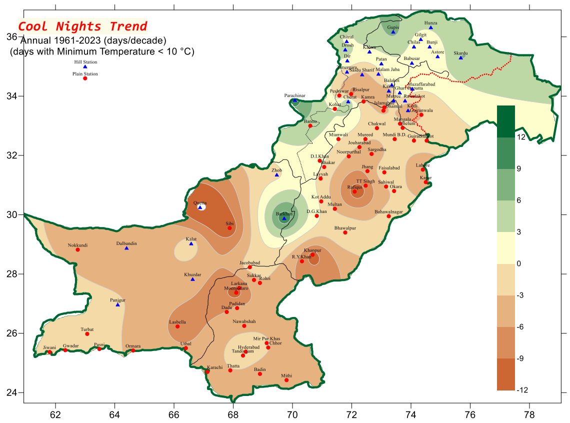


Fig. 5 (a) Trend in the annual number of hot days over 1961-2023, (b) Same as 'a' but for cold nights during.

Tropical Cyclones frequency and Intensity

Tropical cyclones (TCs) are one of the most destructive weather phenomena and biggest threats to life and property of the coastal communities (Wahiduzzaman and Yeasmin 2019). Tropical cyclones can impact in four ways; torrential rains (Knutson et al. 2019), high intensity devastating winds (Zhou et al. 2018), storm surge and coastal inundation (Kohno et al. 2018). Given the increasing global sea surface temperatures and sea-level rise recent research demonstrates that tropical cyclones' intensity is increasing which consequently enhances the strong winds and precipitation. Singh et al. (2020) diagnosed that tracks of TCs over Arabian Sea (AS) are unusual and there is a trend of rapid intensification due primarily to warmer ocean. Being prone to tropical cyclones' impact (direct or indirect), Pakistan coastal areas in recent years were directly struck by TC *02A* (May 1999) which caused about US$6 million worth damages and 700 human lives, TC *Yemyin* (June 2007) which inflicted $560 million worth damages with 950 casualties and TC *Phet* (June 2010) took toll of 44 human lives accompanied with $780 million worth damages across Oman, Pakistan and some parts of India (Sarfaraz and Dube, 2012). In the year 2023, tropical cyclone *Biparjoy* sustaining for 13 days lifespan in the Arabian Sea is an indication that climate change-induced increase in sea surface temperatures (SSTs) coupled with other environmental conditions are potentially set to boost such events in future.

Given this backdrop we also analysed the tropical cycone formation frequency and their intensity over the Arabian Sea over 63-year period 1961-2023 which indicates an increasing trend in frequency of formation (Fig. 6a, dotted line) though statistically insignificant but their intensity is found to be significantly increasing over recent years (Thomas and Lekshmy. 2022; Dasgupta, 2021; IPCC, 2021).

Sea-level Rise

Analysis of sea-level data recorded at Karachi for the period 1906–2020 reveals that the sea level has risen at the rate of 2.02 millimeters per year, for a total of 220.24 centimeters (7.97 inches) in 114 years (Fig. 6b). Other research studies (Quraishee 1988; Rabbani et al. 2008; Chaudhry 2017) using the Karachi tide gauge data have found a sea-level trend of approximately 1.1 mm/yr over the period 1856 - 2000. Spencer et al. (1988) determined it to be 0.97 mm/yr from 1868 to 1946, whereas the studies conducted by Khan et al. (2020) and NOAA (2022) have shown greater ratios of observed sea-level rise at Karachi port of 2.0 mm/yr for 1916 - 2016 and 3.6 mm/yr for 2007 – 2016 respectively.

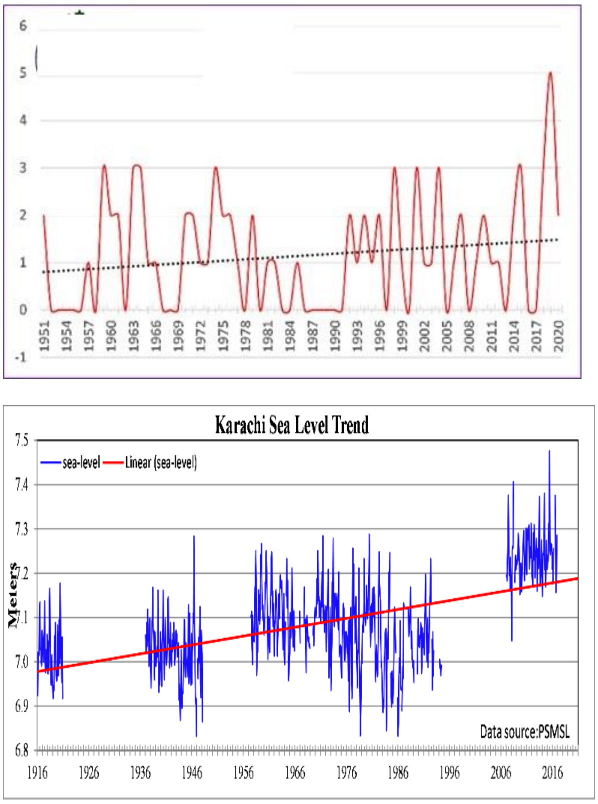


Fig. 6 (a) Annual frequency of Trropical Cyclones over the Arabian Sea, 1961-2020, (b) Monthly mean sea level rise at Karachi, 1906 to 2020.

A 63-year annual and seasonal rainfall analysis revealed that annual and spring (AMJ) rains have statistically significantly increasing trend for Pakistan as a whole. The same analysis at each of 56 stations across Pakistan discovered that monsoon (July-September, JAS) rain has a significantly increasing trend (with 95-99% CI) at Bunji, Chilas, Skardu and Gilgit (Gilgit-Baltistan, GB), Islamabad, Mianwali, Risalpur and Peshawar in north of Pakistan (Table 1, panel 'a') whilst decreasing at Dalbandin and Jiwani (southwest Balochistan) and Garhi-Dupatta (AJK). The winter (DJFM) rain has shown an increasing trend but only at three sites, Dir, Kalat and Mianwali while spring (AMJ) rain has a mixed trend of increasing at some seven places with decreasing at Chitral, Drosh and Garhi-Dupatta. Climatic parameters like precipitation and temperature are crucial for agricultural production (Wheeler and Von Braun, 2013). An increasing JAS-rain at Risalpur and Peshawar is a precarious sign for the area, commonly recognized as the Peshawar Valley comprising of six districts having a population of about

11.9 million and area of 7176 Km^2 (PBS, 2017). This region has not experienced the floods in the past but the rainfall trend exposed the region evolving as susceptible to deluges and adverse effect to local Kharif crops. The occupations of huge populace of the basin is agronomy reliant, which may suffer adversely due to excessive rain-induced floods. On the other hand, an increase in winter and spring rains may prove beneficial for Rabi and other seasonal local crops. However, a decrease in AMJ-rain in upper KP and Kashmir valleys may prove adverse to the Rabi crops because of their late-season harvesting. The analysis of snowfall revealed a decrease in number of snow-days by 6-8 days at snow-receiving mountainous areas in KP and GB (Fig. 3b). The declining snow trend might pose an antagonist effect on rivers flow and water reservoirs because snowfall and perennial ice over high mountains, Himalaya, Karakorum & Hindukush (HKH) drives the rivers flow in following spring/summer season, which in turn runs the lifeline of irrigation, hydroelectric power generation and domestic water use.

The analysis of annual mean, maximum and minimum temperatures (T_{mean}, T_{max}, and T_{min}) has also indicated significantly upsurge trend across Pakistan. The same analysis at every of 56 locations has shown a noteworthy increase in all three temperature indices in the south and northeast Pakistan (Table 2) except few sites; Bunji, Cherat and Parachinar which have observed a declining tendency. The increasing annual mean temperature in the southern Pakistan may escalate the infertility of the region and damage the indigenous crops; over northeast Pakistan, the repercussion for agronomy could be antagonistic. At country level, virtually alike tendency of increase in T_{mean}, T_{max} and T_{min} since 1998 onwards concurs with worldwide warming pattern. Rising T_{mean} over GB and Upper KP can speed up the glaciers melt leading to frequent Glacial Lake Outburst Flood (GLOF) events that may inflict a calamitous situation in the slender but compactly populous valleys. A substantial rise in maximum temperature may proliferate the heatwaves, as the one Karachi has suffered in 2015 and 2018 and country's most plains in 2022. The prolonged 2022 heatwave episode has been attributed to climate change by a study conducted by the *World Weather Attribution* (Zachariah et al. 2023). T_{max} increasing tendency can also be harmful for crops yield, for instance; the heat strain, caused by unexpectedly high temperatures, in 2010 resulted in early ripeness of wheat specks thereby reducing wheat yields by 13% in Pakistan (Rasul et al. 2011). Likewise, the yearly minimum temperature too showed an upsurge trend at several distinct locations indicating lessening of winter season, which is an indication of dwindling winter and increasing summer season. Therefore, climate change resilience pursuing the National Climate Change Adaptation Plan must be prioritized to assist the local populations of exposed region of KP and GB.

The studies have demonstrated that the climate and weather extremes have become more severe owing to global warming with each fraction of degree of warming affects the social justice (Ref. section 1.1) and access to food and fresh water, extinction of creatures and vegetation/ floras, and marine life.

Anthropogenic climate change has its impacts manifold and a potential threat to global food production is a matter of concern (UNFCCC, 1992). The observations and evidence specifies adverse effects of climate change on crop productivity around the world (Schlenker & Lobell 2010; Lobell et al. 2011b; Moore & Lobell 2015). Predominantly the harmful weather events, droughts and heatwaves, are serious peril to crop productivity (Lesk et al. 2016; Schauberger et al. 2017; Ray et al. 2015). Hostile effects from tropical cyclones, with related fatalities and harms have amplified because of sea level upswing and increasing heavy precipitation. Natural and human systems are impacted from ocean acidification, sea level rise or locally decreasing precipitation that are actually the result of anthropogenic climate change (IPCC, 2021).

Conclusion

increasing in recent years but insignificantly, however, their intensity is showing a significant rise and so is the sea level (Fig. 6a, b). To summarize, the Pakistan climate has warmed considerably, rainfall shows a mixed trend and cyclone intensity and sea level are rising. To substantiate these results, plan is to undertake the further research by incorporating the climate data from more locations and cross-validate that with data from international climate centers. Moreover, a robust climate change adaptation is recommended to reduce the risks and mitigate the potential losses of lives and property.

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