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Changing trends of climate in Gilgit-Baltistan (GB) from 1955 to 2018

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K E Y W O R D S

Precipitation

Temperature

Gilgit

Skardu

Summer

Spring

A B S T R A C T

This research aims to evaluate the long-term changing trends of climate over Gilgit-Baltistan (GB) from 1955 to 2018, over 64 years of observation data from six major stations in GB. For this purpose, Mann-Kendall and Sen's Slope Estimator tests were employed to examine the seasonal and annual trends in key climatic parameters, temperature, and precipitation. Results signify an overall increasing trend in annual temperature at most stations, with statistically significant warming trends at Skardu and Astore at the same rate of 0.02 ºC/year; Bunji showed a significant declining trend. Seasonal analysis revealed a consistent rise in winter temperatures at most stations, while summer temperatures declined, except at Astore, where slight increasing trend (0.01 ºC/year) was detected.

Precipitation trends revealed spatial variability, with a significant increasing trend in Gupis, mostly during Spring, Summer, and Winter, with the highest increasing rate of 1.24 mm/year. Whereas Astore and Chilas stations showed non-significant decreasing trends in annual precipitation, -0.80 mm/year and -0.13 mm/year, respectively. The findings of this research revealed a shifting climatic regime in GB, characterized by increased seasonal precipitation and warmer winters, which has prime implications for glacier mass balance and downstream water flow. These findings specify critical scientific evidence for climate adaptation strategies and water resource management planning in the Upper Indus Basin (UIB).

1. Introduction

Global warming and Climate Change (CC) are unequivocal, and their impacts are felt everywhere around the world. The mountain ecosystems, such as Gilgit-Baltistan (GB) hosting the world's third-largest ice mass in the form of thousands of glaciers, are highly vulnerable to global warming. In Pakistan, significant changes have been recorded in rainfall and snowfall amounts, their spatial and temporal distributions. Due to the rugged terrain of GB, climate change has not taken place uniformly. The Karakoram anomaly (the unusual behaviour of the glaciers in the Karakoram ranges) demands detailed analyses of climate data. These mountains host the water towers of Pakistan, which feed water to the region's major irrigation system and the water reservoirs. The strong build-up of GHGs (Greenhouse Gases) in the atmosphere traps more heat, which triggers the melting of these water towers by increasing temperature [1, 2, 3].

Pakistan is an agricultural country; its economy depends on agriculture, which is vastly dependent on IBIS (Indus Basin Irrigation System). This system serves twenty-two million hectares and contributes 85% of the production by irrigated land [4]. The water balance and hydrological cycle of GB will be revised by climate change. The process of runoff generation will directly influence the changes in precipitation and temperature. Thus, the temporal and spatial anomaly in the availability of water distress industries, agriculture, and developmental works down the streams. An increase in extreme events often leads to landslides, rockfall, flash floods, and erosion, which eventually affect livelihoods and human health [2].

From the perspective of climate change, there is a dire need to capture the varying patterns of temperatures and precipitation over GB.

In Pakistan, summer and winter make the major contributions to the annual total precipitation. There is a variation from 500 mm to 800 mm per year in total annual precipitation. During winter, the mid-latitude westerly waves travel through the lower latitudes, and their channels normally outspread down to 35 °N. As a result, the northern parts of Pakistan received significant snowfall at high elevations and rainfall at lower elevations. During both summer and winter, the northern areas of the country received sufficient precipitation, but the southern parts received only 50% of the amount received by the northern parts [5].

The melting of accumulated snow and ice on upper mountains occurs during the summer season and sustains river flow for agricultural purposes, power generation, and industrial requirements. Additionally, winter precipitation brings considerable rainfall over sub-mountainous and plain areas [6].

GB is the foremost water source of the main rivers of Pakistan [7]. Wide-ranging impacts of climate change, increased variability in water availability, reduced agricultural productivity, increased frequency of extreme events, GLOF (Glacial Lake Outburst Flood) events, increased river and coastal erosion, and seawater intrusion, are expected in Pakistan [8]. The changing climate also directly or indirectly affects biodiversity and its habitats [3]. Fluctuating tendencies in temperature, precipitation, and extreme events in GB fetched floods in upper stream tributaries and the River Indus, which damaged infrastructure, eroded the riverbank, and affected populations living along the stream.

The major sources of precipitation are snow and rain during winter and spring. The climate is arid if precipitation is 80 to 200 mm, semi-arid if it is 200 to 350 mm, and sub-humid if it is 350 to 500 mm, which is the upper limit of precipitation in GB. Most valleys of GB receive minute precipitation and are recognized as cold deserts. At the valley level, the standard rainfall is under 200 mm, but snowfall mostly occurs above 4,000m and increases with elevation. The effects of mountain climates under extensive patterns of global rotation are associated with the continent's large-scale and longitudinal position in the surrounding ocean. During the spring and winter, the Karakoram region is disturbed by the climate system, which originates primarily in the Mediterranean or Caspian region, and by strong windstorms in the summer pre-monsoon season and monsoon system [3, 8].

Multiple research projects conducted in the Upper Indus Basin (UIB) identified that the warming trend of annual temperatures up to 5% (1 °C) has increased the runoff of rivers Shoyk (at Yogu), Shigar (at Shigar), and Indus (at Kachura) has been increased up to 9%, 7% and 5% respectively [9, 10].

There is a dire need to assess the annual and seasonal trends of temperature and precipitation to trace their impact on energy sectors and water resources of the region. The specific aim of this study is to explore the annual and seasonal trends in temperatures and precipitation over GB so that policymakers can devise better policies.

2. Data and Study Area

Daily data of two major meteorological parameters (temperature and precipitation) over the period of 64 years (1955 – 2018) from the six meteorological stations (Astore, Bunji, Chilas, Gilgit, Gupis, and Skardu) located in Gilgit-Baltistan, as shown in Fig.1, were acquired from PMD (Pakistan Meteorological Department), for the assessment of climatic trends.

The PMD records daily and continuous data following the World Meteorological Organization (WMO) standards. PMD has a suitable number of observation stations throughout Pakistan and Gilgit-Baltistan, which provide good coverage of meteorological data. All data goes through quality control tests, incorporating scrutiny, tabularization, and authentication. Missing data is part of the data. PMD manages missing data by interpolation with nearby stations and historical data, by replacing the mean value, or using a regression method. The data gaps may be because of instrumental error and station relocation. Missing data handling is the responsibility of the Climate Data Processing unit at PMD Head Office Karachi, which uses automated and manual methods. Our data did not include any missing data, as PMD provided a set of standard data.

Although PMD provides homogeneous data, we also applied a graphical homogeneity test to all data sets to further confirm data homogeneity. By using these datasets, monthly, seasonal, and annual temperatures and precipitation were calculated, and a trend analysis was performed. GB is found between the mighty mountain Himalaya-Karakoram and the Hindukush (HKH) ranges. After the polar regions, this fragile region is the world’s third-largest ice mass, highlighting its importance to global sea level change. The Indus River and its tributaries play a vital role in the country's economic, agricultural, and energy sectors. The changing behaviours of its glaciers, biodiversity, and climate are attracting nationally and internationally recognized researchers to these regions. Researchers have been researching climate change and its impacts on glaciers and other sectors of life in GB [11].

After the China-Pakistan Economic Corridor (CPEC) project, this region became the backbone for the economic development of the whole of Asia. The rapid development in the region also changes the environmental conditions of GB. These changes are highly affecting every sector of life. So, there is a dire need to assess these environmental changes spatially and temporally.

3. Methodology

The consistency analysis of the datasets was executed on monthly average temperatures and total precipitation. It was assessed by using graphical analysis. The area averages of both climate parameters (temperatures and precipitation) series were calculated by using monthly data from all stations. Annual and seasonal climatic conditions were calculated by using the same data sets.

There are multiple statistical techniques through which trend analysis can be conducted. One of the widely used method is the MK test, which is a non-parametric test, so the outliers in the data do not affect the results [12, 13, 14]. This test has low sensitivity to abrupt breaks due to inhomogeneous time series. It can manage non-normal hydrological data. Multiple researchers and scientists assessed trends in various hydro-meteorological parameters by using the MK test [15, 16].

In this study, the MK test was applied to discover the statistical significance of trends in two major climatic parameters, temperature and precipitation data. The MK test is a non-parametric and widely used test for trend analysis in time series data, especially in climatology and hydrology. It is used to detect monotonic trends in time series data without assumptions of any distribution, such as normality. This test is more powerful against missing data, data outliers, and non-normal distributions, which makes it the best choice for the analysis of meteorological data. For the application of the MK test, it is assumed that the data are independent and autocorrelated or serially correlated. The trend is assumed to be either consistently increasing or decreasing over time. The MK test does not detect non-monotonic trends in data [17].

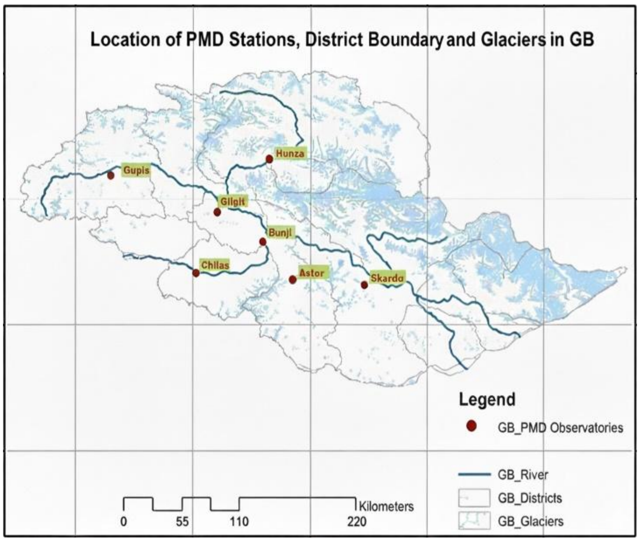

Fig. 1. Study Area and Location of the Meteorological Stations.

The slope of an existing trend can be calculated by applying Sen's Slope Estimator [18]. Sen's Slope Estimator (SSE) is used to calculate changes in temperature and precipitation. The purpose of trend testing is to decide whether there is a statistical trend (rising or falling) in the data or not [18]. Parametric or non-parametric tests can be employed to find whether the trend is statistically significant or not [15].

Microsoft Excel template MAKESENS has been used to perform MK and Sen's Slope Test, a widely used package for discovering and investigating trends in temperature and precipitation data [12, 20, 21].

4. Results

Tables 1 and 2 show that over GB, annual temperature and precipitation differ by location. Throughout the bracketed period (1955-2018), the annual average temperature varied from 9.77 oC/year to 20.24 oC/year, while mean precipitation changed from 138.51 mm to 453.76 mm. Gilgit and Astore simultaneously remained the warmest and coldest areas in the region, while maximum precipitation was recorded in Astore and minimum in Gilgit. To give a quantitative description of the key features of individual regions, descriptive statistics have been applied. The highest annual mean temperature has been recorded (20.24 oC/year) at Chilas, and the lowest recorded (9.77 oC/year) at Astor. The temperature records at Gupis have the highest standard deviation (0.89), but the data recorded at Gilgit station have the lowest standard deviation (0.56).

The MK test results have shown rising trends in annual temperatures in five regions, i.e., Astor, Chilas, Gilgit, Gupis, and Skardu, and a falling trend in Bunji. The annual temperature at Astore and Skardu significantly increased, while it significantly decreased at Bunji. It is also shown that the annual precipitation has increasing trends at all stations excluding Astore and Chilas, where it has decreased, but not significantly. Annual Precipitation has decreased non-significantly in Astore (-0.80 mm/year) and Chilas (-0.13 mm/year) (Tables 1 & 2).

The summary of seasonal trends in mean temperatures and precipitation in GB for 60 years (1955 - 2018) has been given in Figs. (1 & 2). These figures show that during all seasons, Chilas and Astore were simultaneously the warmest and coldest areas of the region. At all stations, the largest amount of precipitation occurred in spring and the minimum in the autumn season. During spring, the mean precipitation varied from 62.7 mm to 209 mm, and during autumn it changed from 18 mm to 62.5 mm (Table 4).

Table 3 shows that there were upward trends in winter temperatures at all stations except Gupis, which showed that the winter season of the GB region became warmer during the given period. While the summer season showed downward trends of temperatures at all stations except Astor, where the summer mean temperature increased non-significantly. It is also revealed that the autumn temperatures of Astore, Bunji, and Gilgit have increased significantly.

Table 4 reveals that during the study period, summer precipitation has increased over the GB, which shows the approach of the monsoon in this region. Autumn and winter precipitation have also increased trends at all stations except at Astore, where it has decreased non-significantly. Spring precipitation has a downward trend for all regions. These results declare that GB will receive more seasonal precipitation in the future.

Table 5 displays the seasonal means, corresponding standard deviations, and the temperature and precipitation range for the whole GB from 1955 to 2018. This found that in winter, the mean temperature falls below the freezing point, and during summer it rises above 30 oC. The maximum deviation in the observation was recorded in the spring season. The maximum rainfall was detected for the spring season, and the minimum was seen in the autumn season.

Seasonal percentages of mean precipitation are given in Fig. 3. 45 % of the total precipitation occurred during spring, and 13 % was received in the autumn season. This shown that the autumn season stayed the driest. 21 % of the total annual precipitation is recorded during the winter and summer seasons.

Table 1.

Descriptive Statistics and Trends of the Annual Mean Temperature.

Stations	Latitude	Longitude	Average Altitude a.s.l. (meters)	Mean temperature (ºC)	Std. Dev.	Range of Temp. (ºC)		MK Test (Z)	Trends	Results	SSE Change in Temp. (ºC / year)
						min	max				
Astore	35º20′	74º 54′	2168	9.77	0.69	3.97	15.60	3.17	↑	Sig.	0.02
Bunji	35º40′	74º 38′	1372	17.72	0.77	12.26	23.84	-2.64	↓	Sig.	-0.02
Chilas	35º25′	74º 06′	1251	20.24	0.65	14.90	26.38	1.77	↑	NS	0.01
Gilgit	35º55′	74º 20′	1460	15.94	0.56	7.82	23.85	1.31	↑	NS	0.01
Gupis	36º10′	73º 24′	2155	12.40	0.89	6.10	18.80	1.04	↑	Sig	0.02
Skardu	35º18′	75º 41′	2210	11.66	0.73	4.89	18.46	2.86	↑	Sig.	0.02

Table 2.

Descriptive Statistics and Trend of Total Annual Precipitation.

Stations	Mean Precipitation (mm)	Std.Dev.	Ranges of precipitations (mm)		MK Test (Z)	Trends	Results	SSE change in Precipitation (mm / year)
			Min.	Max.				
Astore	453.76	118.42	225.60	748.30	-0.63	↓	NS	-0.80
Bunji	155.83	60.47	65.30	339.40	1.54	↑	NS	0.71
Chilas	190.22	82.97	36.20	471.90	-0.16	↓	NS	-0.13
Gilgit	138.51	49.04	40.70	266.00	1.35	↑	NS	0.51
Gupis	187.41	132.05	5.30	675.60	1.52	↑	NS	1.24
Skardu	227.05	98.24	68.30	547.00	0.74	↑	NS	0.47

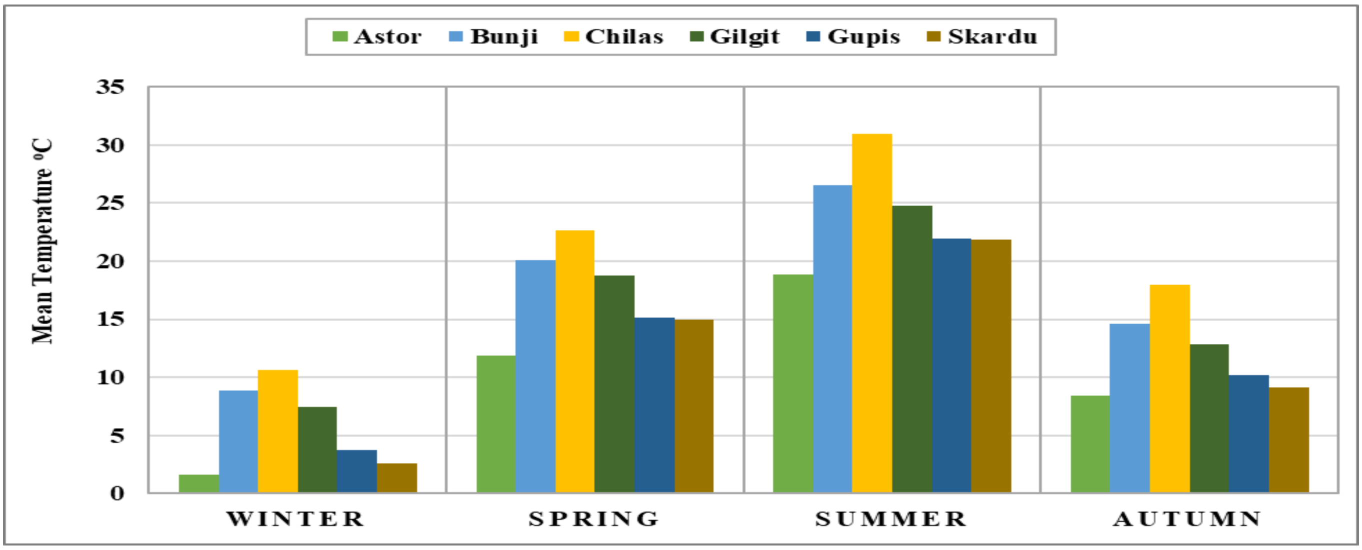

Fig. 2. Seasonal temperatures in GB.

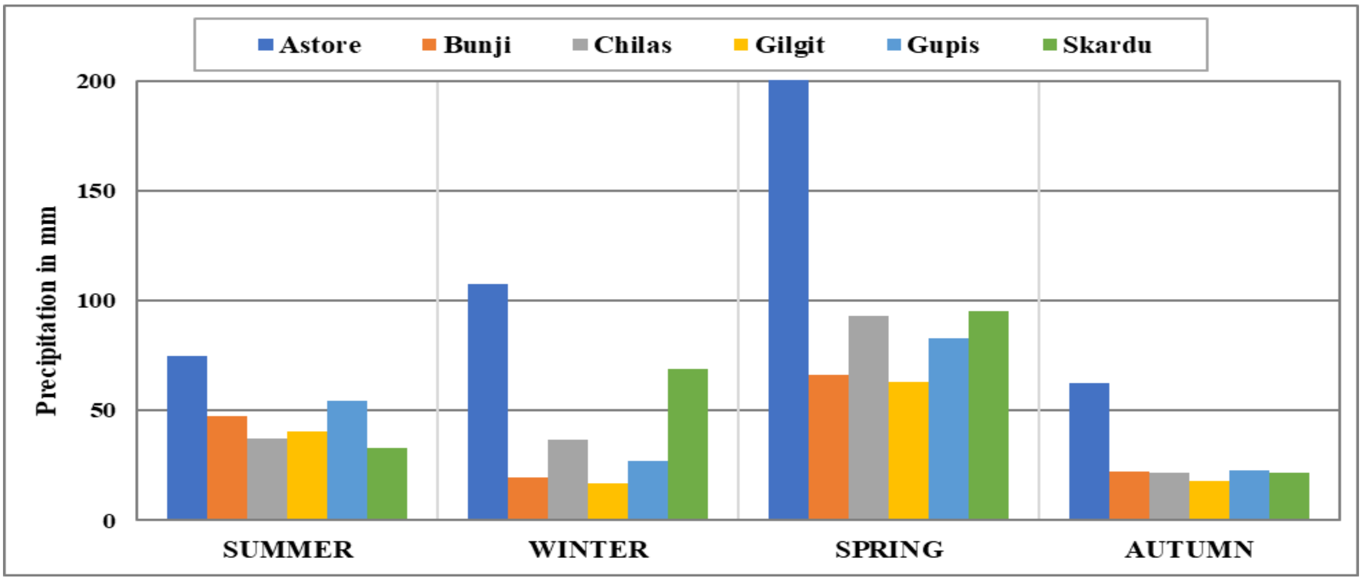

Fig. 3. Seasonal Precipitations in GB.

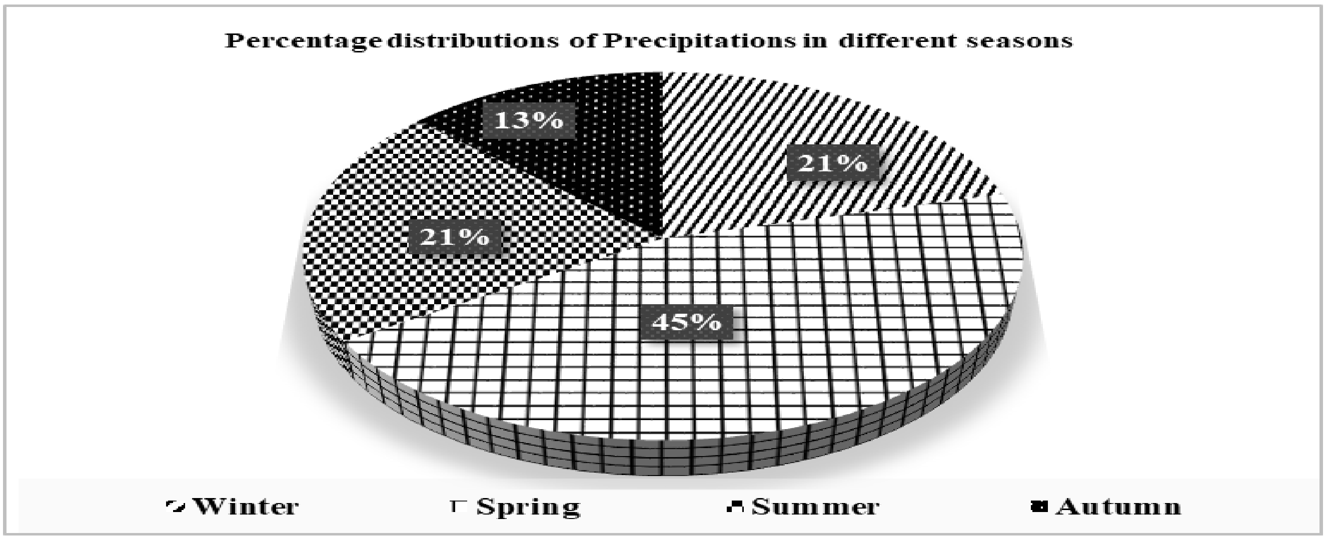

Fig. 4. Season Wise Percentage of Mean Annual Precipitation in GB.

Table 3

Seasonal Mean, Standard Deviations, Ranges and Trends of Temperatures.

Stations	Seasons	Mean Temp. (ºC)	Std. Dev.	Range of Mean Temp. (ºC)		MK Test (Test Z)	Trends	Results	SSE Change in Temperature (ºC/year)
				Min.	Max.				
Astore	Winter	1.63	0.94	-3.49	6.75	2.82	↑	Sig.	0.05
	Spring	11.83	1.40	5.94	17.71	1.19	↑	NS	0.03
	Summer	18.88	0.69	12.41	25.35	0.14	↑	NS	0.01
	Autumn	8.41	0.92	2.11	14.71	2.12	↑	Sig.	0.034
Bunji	Winter	8.83	0.66	3.17	14.49	3.72	↑	Sig.	0.04
	Spring	20.07	1.39	13.59	26.55	0.51	↑	NS	0.02
	Summer	26.49	0.96	19.53	33.46	-0.29	↓	NS	-0.01
	Autumn	14.61	0.79	7.15	22.07	2.05	↑	Sig	0.03
Chilas	Winter	10.63	0.63	4.96	16.29	1.43	↑	NS	0.02
	Spring	22.62	1.73	16.46	28.78	-0.09	↓	NS	-0.01
	Summer	30.92	1.01	24.71	37.12	-2.03	↓	Sig.	-0.04
	Autumn	17.93	0.76	11.15	24.72	-0.08	↓	NS	0.00
Gilgit	Winter	7.43	0.66	0.29	14.56	3.83	↑	Sig.	0.04
	Spring	18.75	1.21	10.43	27.07	0.79	↑	NS	0.02
	Summer	24.78	0.71	15.35	34.21	-0.91	↓	NS	0.02
	Autumn	12.80	0.72	3.19	22.41	2.31	↑	Sig.	0.03
Gupis	Winter	3.72	1.41	-2.06	9.50	-0.23	↓	NS	-0.01

	Spring	15.14	1.65	8.80	21.48	0.43	↑	NS	0.01
	Summer	21.96	1.38	14.99	28.93	-1.57	↓	NS	-0.03
	Autumn	10.22	1.51	3.39	17.04	1.29	↑	NS	0.03
Skardu	Winter	2.62	1.09	-3.66	8.91	0.91	↑	NS	0.02
	Spring	14.94	1.12	8.05	21.85	0.11	↑	NS	0.01
	Summer	21.85	0.89	13.81	29.89	-2.00	↓	Sig.	-0.04
	Autumn	9.14	0.85	0.79	17.48	-0.29	↓	NS	-0.01

Table 4.

Seasonal Mean, Standard Deviations, Ranges and Trends of Precipitations.

Stations	Seasons	Mean Precipitations (mm)	Std. Dev.	Ranges of Precipitation (mm)		MK Test (Test Z)	Trends	Results	Sen's Slope Estimate Change in Precipitation (mm/year)
				Min.	Max.				
Astore	Winter	107.4	61.3	0.3	276	0.16	↓	NS	0.12
	Spring	208.9	82.7	46.8	367.2	-2.11	↓	NS	-1.33
	Summer	74.8	35.5	21.1	203.6	0.39	↑	NS	0.09
	Autumn	62.5	45.9	0.6	170.6	-0.97	↓	NS	-0.29
Bunji	Winter	19.7	17.6	1	185	1.30	↑	NS	0.13
	Spring	66.2	41.3	12.3	179.2	-0.75	↓	NS	-0.24
	Summer	47.4	32.3	10.2	157	1.31	↑	NS	0.33
	Autumn	22.4	22.8	0.0	124.8	0.37	↑	NS	0.05
Chilas	Winter	36.5	27.3	0	117.9	0.63	↑	NS	0.12
	Spring	92.8	60.1	13.1	276.0	-1.03	↓	NS	-0.40
	Summer	37	26.5	10.4	152.7	1.86	↑	NS	0.32
	Autumn	21.6	28.3	0.0	146.2	0.16	↑	NS	0.02
Gilgit	Winter	16.8	12.9	0	45.5	0.54	↑	NS	0.04
	Spring	62.7	39.4	15.7	164.4	-0.13	↓	NS	-0.04
	Summer	40.2	24.6	16.2	144	1.37	↑	NS	0.22
	Autumn	17.9	17.3	0.0	102.4	1.10	↑	NS	0.10
Gupis	Winter	26.9	32.7	0.0	164.2	0.56	↑	NS	0.08

	Spring	83.1	83.2	0.0	432.4	0.43	↑	NS	0.15
	Summer	54.5	42.8	2.3	204	2.03	↑	Sig.	0.51
	Autumn	22.9	32.2	0.0	109.7	0.45	↑	NS	0.05
Skardu	Winter	68.8	52.9	4.8	198.7	2.20	↑	NS	0.71
	Spring	95.2	59.4	13.1	295	-0.51	↓	NS	-0.17
	Summer	33.2	22.3	6.4	95.4	0.90	↑	NS	0.14
	Autumn	21.8	23.4	0.0	114.5	0.43	↑	NS	0.04

Table 5

Seasonal Mean Temperature and Total Precipitation in GB.

Province	Seasons	Mean Temp. (ºC)	Std. Dev. Temp. (ºC)	Mean Temp. Range in ºC		Mean Precipitations (mm)	Std. Dev. Min.	Ranges of Precipitations (mm)	
				Min.	Max.			Min.	Max.
Gilgit-Baltistan	Winter	5.81	0.69	-0.13	11.75	46.0	35.5	19.0	276.0
	Spring	17.23	1.34	10.54	23.91	101.5	54.3	7.0	432.4
	Summer	24.15	0.75	16.84	31.49	47.9	15.2	6.0	204.0
	Autumn	12.18	0.68	4.63	19.73	17.0	12.6	0.6	170.6

5. Discussion and Conclusion:

The sustainable water resources in the UIB are vital for the water reservoirs of Pakistan, which are used to store and release water to the planned areas when needed. The Indus Irrigation System plays a pivotal role in sustainable agriculture and the energy sector of Pakistan, which is regulated through the Tarbela and Mangla dams. Both are fed by snow and glacier meltwater. Any change in the temperature and precipitation patterns of Gilgit-Baltistan changes the sustainable water supply to these dams. This will have an intense effect on millions of people living downstream [6].

This research revealed increasing trends of monthly, seasonal, and annual temperatures & precipitation in Gilgit-Baltistan over a 65-year study period (1955-2018). The rising tendency in annual temperature over the whole of Pakistan was also mentioned by Chaudhry in 2019. He also mentioned a 25% increase in annual precipitation over Pakistan, with an expansion of aridity in the northern parts [8].

Annual temperature and precipitation at various locations have significant variations. Consistent and non-significant rising trends in annual temperature and precipitation over GB from 1981 to 2012 were found by Raza et al. in 2016 [11]. The warming trend of the winter season over the whole region of GB may affect the solid precipitation trend, which seriously decreases the snow and ice areas in the region. The snow and ice areas in the form of glaciers are the major source of water for the Indus River; any change in these areas will change the water supply to the stream.

Astore showed a negative trend in annual precipitation with 5% significant level. This will affect the water flow in the Astore River. In the remaining region, there were increasing trends in the annual precipitation with the same significance level of 5%. Significant changes in seasonal and annual precipitation were found in Gupis. Hussain et al. also confirmed the same result in 2018 [22]. Confirming the increasing trend in precipitation, Nir et al. [23] found an average annual precipitation of about 500 mm over the Indus Basin and an increase in mean precipitation of about 15% between 1891 and 2016.

The results of this study also coherent the statistical trends shown by Khalid et al. [23] and Hartmann et al.

[25] for the River Indus Basin. The outcomes of this research are also consistent with the results of Imran [26], Steinbauer [27], Rasul [5, 28], Dimri [29], and Immerzeel [30], who found a significantly increasing trend in winter precipitation over extreme north of Pakistan.

These changing trends in temperature and precipitation are due to global climate change. Global warming and climate change are primarily changing the regional climate dynamics. The unique geographic location of this region, and human activities such as deforestation and constructional developmental works are also causing changes in the trends of two major climatic parameters, temperature and precipitation of the region.

Based on the findings of this research, it is concluded that there is seasonal shifting in GB as the winter over the whole GB has warmed, and that of summer temperature falls from the mean temperature. Total annual precipitation has increased over GB during the study period. GB is likely to receive more precipitation during summer and winter. The characterized increase in seasonal precipitation and warmer winters has serious implications for the glacier mass balance and water flow in tributaries. These changes in temperature and precipitation may cause water and water-related disasters such as droughts, GLOF events, floods, landsliding, and land erosion. Considering these situations, adaptations and mitigation strategies must be formulated to minimize risks in the future. Moreover, these findings further specify critical scientific evidence for climate adaptation strategies and water resource management planning in the Upper Indus Basin (UIB).

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