

Indicators of Climate Change in Kabul City Afghanistan

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DOI: <https://doi.org/10.51583/IJLTEMAS.2025.1408000131>

Abstract: This study analyses trends in rainfall, temperature, and humidity over a 15-year period (2006–2020) to investigate the effects of climate change on Kabul City. The Afghanistan Meteorological Department provided the data used to evaluate long-term trends and spatiotemporal variability. The findings show considerable climatic variability, with monthly rainfall generally rising but noticeably falling during the monsoon season. With the exception of the summer and monsoon seasons, when increases were noted, temperature study shows that monthly maximum temperatures are decreasing for the majority of the months. Trends in humidity indicate a steady yearly increase with noticeable seasonal variations. Two severe drought events (2007–2008 and 2016–2018) and one intermediate rainy spell (2011–2014) are highlighted in the precipitation record, highlighting the insufficiency of water resources to satisfy the demands of Kabul's rapidly expanding urban population. A negative water balance has been exacerbated by over-extraction and inappropriate water usage, which has weakened urban resilience, especially in agriculture, and increased the likelihood of water scarcity. In addition to offering insights to enable adaptation methods in Kabul's urban climate environment, the study highlights the urgency of evidence-based policies for sustainable water resource management.

Keywords: Kabul city, Climate Change, Rainfall, Temperature, Precipitation, Drought, Rainfall Anomaly, Trend line, Annual Average

I. Introduction

This research explores the spatiotemporal patterns of Afghan drought from 1980-2017 against the backdrop of severe food insecurity fueled by recurrent conflict. In applying the monthly, seasonal, and annual scales of the Standardized Precipitation Evapotranspiration Index (SPEI), this study examines characteristics of drought, including distribution, frequency, duration, and intensity, over the 189 sub-catchments. Data from temperature and precipitation station records were used to calculate SPEI indices for each sub-catchment. The results show significant spatial variability in drought characteristics among sub-catchments and temporal variability in years and seasons. The results highlight the 2000s as the driest decade and 1999-2022 as the longest-lasting drought period within the study period. The 2000-2001 water year was unusually severe, with drought conditions across the country varying between "severe" and "extreme." More than half of the country, more than 53% of sub-catchments, had the highest severity of drought ever observed at this time, and about 58% experienced "very frequent" or "extremely frequent" drought, i.e., for 7-10 months. Intermittent droughts of different severity and duration are reported for 2004, 2006, 2008, and 2011. A clear trend is observed towards deepening drought and its longer durations, spreading geographically from southeastern parts towards the north and the central regions of the country. This study adds important sub-catchment-level information on meteorological drought attributes in Afghanistan, filling an important knowledge gap. The results improve the knowledge of climate change effects on drought dynamics and offer useful insights for successful catchment planning, thereby enabling adaptation and mitigation against future drought occurrences.

II. Study Area

Kabul City is the capital and biggest city of Afghanistan, situated in the central region of Afghanistan, with a population of 4627304 in 2021 [6], with a size of 1023 km². It is encircled by the Paghman series mountain in the west, Qurugh Mountain in the south, Sher Darwaza, Asmaie, and Ali Abad Mountains in the centre and north of the city. Koh-e Asmai, or "Asamayi

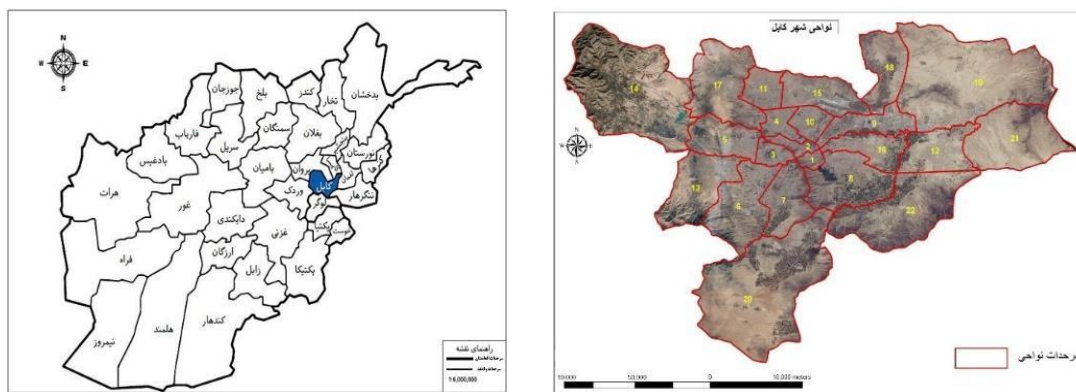


Figure 1: Topographic District Map of Kabul City

Source: Compiled by Authors'

Mountain," lies in the centre of the city. It is one of Kabul's most noticeable landmarks, rising to a height of about 2200 metres above sea level. It lies to the east of the city centre, dividing the Shar-e-Naw and Wazir Akbar Khan neighbourhoods. Koh-e Asmai plays an important role in influencing the weather patterns of Kabul. The mountain serves as a shield to the westerly winds that are dominant and bring moisture from the Mediterranean and other areas in the west. This creates a semi-arid climate in Kabul, with hot summers and cold winters. Kabul is located at a height of 1,800 m above sea level in a narrow valley between mountains. The city is linked to Kandahar, Herat, and Mazar-e-Sharif by a ring highway extending through the length of the country. It is also the beginning of the primary road to Jalalabad and onward to Peshawar, Pakistan. The Kabul Province is bounded by Logar-Wardak provinces in the southeast, Parwan and Kapisa to the north, and the Ningrahar and Laghman provinces to the west. Kabul is a dry and semi-dry climate, and in winter, it experiences precipitation in the form of snow. Summer, from May to August, is marked by extremely low humidity, which brings relief from the heat. Autumn is dry and warm, beginning in September and finishing in October. Winter is cold but mild, from November to March. Spring in Kabul begins in March and is the season with the highest rainfall of the year.

III. Materials and Methods

The precipitation data were obtained from the Afghanistan Meteorological Department (AMD); initially, the large amount of precipitation data for at least thirty years was required to provide a clear and consistent picture of the past precipitation condition of the study area. But because of the civil war and instability in Afghanistan, there were no consecutive records of precipitation data in the weather stations, or some observed data records were missing, which caused an error in analysis. Starting from 2005, the Afghanistan Meteorological Department (AMD) recorded the precipitation data consecutively and regularly, but these data were utilized in this study.

Precipitation was on a daily record; rainfall was summed daily and then totaled yearly for analysis. To identify whether precipitation had increased or decreased, trend lines were graphed, and charts and graphs were constructed.

Linear regression equation formula is utilized to examine the rate of changes in precipitation. Its general form is:

$$y=ax+b \quad (1) [8]$$

In this representation y = precipitation (mm), a = gradient, x = time series, and b = previous precipitation. The trend value is correlated to the gradient. There are three possibilities: a) if the gradient is greater than zero - the trend is positive (increasing); b) if the gradient is less than zero - the trend is negative (decreasing); c) if the gradient is equal to zero - there is no trend [9]. The standard deviation is a means to calculate the dispersion, of a set of different data points, from its mean, and was used to calculate the dispersion of precipitation data from its mean in each year [10] and determine how dry or wet a year was years in the study area, and is defined as:

$$\sigma = \sqrt{\frac{\sum (X - \bar{X})^2}{N}} \quad (2)$$

Precipitation Patterns

Precipitation pattern changes are another significant pointer to climate change in Kabul. Although the general precipitation trend is not as definitive as temperature rise, a number of studies offer explanations on changing rain patterns. [6] established that 50% of precipitation in Kabul is received during winter with annual variability. The study also reports a slight increase in precipitation of 0.64 mm/yr, which is not enough to counterbalance the impacts of urban warming and water consumption. [6] The small rise is not enough to serve the expanding needs of a high population density. The study in [6] also identifies two extreme drought periods (2007-2008 and 2016-2018) and one moderate wet period (2011-2014) in Kabul City during the 15-year study period. [7] employs the Coordinated Regional Downscaling Experiment (CORDEX) program data to make future precipitation change projections in the Kabul basin. The research concludes that certain regional climate models (RCMs) exhibit widely different precipitation patterns, both spatially and temporally, even when forced by the same global climate models (GCMs). Nevertheless, an ensemble of the better-performing RCMs indicates a declining trend in future precipitation under both RCP 4.5 and RCP 8.5 scenarios [7]. This declining trend is notable especially in the central regions of the basin. These results are indicative of the complexity of regional precipitation modeling as well as potential future water shortage. The analysis by [8] gives an overview of more general future precipitation changes in Afghanistan under different shared socioeconomic pathways (SSPs). The analysis utilizes bias-corrected CMIP6 GCM simulations and demonstrates that increased emission scenarios (SSP3-7.0 and SSP5-8.5) model increased precipitation for most of Afghanistan, especially in summer. There is, however, also a predicted reduction in precipitation in the northwestern part in some scenarios, and this serves to emphasize the spatial heterogeneity of the projected changes. [8]

Research conducted by [9] analyzed meteorological and agricultural droughts across the Chitral-Kabul River Basin (CKRB) during 2000-2018 through a range of drought indices. Findings identify the most extreme years to have been 2001 and 2018 and, though the spatial variation between occurrences exists, a downward general trend was shown for both meteorological and agricultural droughts. The trend, however, is anticipated to hold up to the year 2030 [9]. This accentuates the continuing susceptibility of the region to drought following the occurrence of some short-term fluctuations. The research by [10] also examines the spatiotemporal behavior of drought attributes in Afghanistan on the sub-catchment level utilizing the Standardized Precipitation Evapotranspiration

Index (SPEI). The study finds great differences in drought frequency, severity, duration, and distribution across the nation and over time, with the 2000-2001 water year being the driest in recent history. The research also finds a trend towards more severe and longer-lasting droughts in the central and northern parts of Afghanistan. [10] Afghanistan's precipitation patterns over the last century have fluctuated regionally, with minimal areas of the country experiencing statistically significant changes. Conversely, increases in the intensity of droughts in some areas of the country have been particularly notable. Between 1901 and 2010, southern Kandahar, Helmand and Nimruz provinces' drought intensity heightened considerably in their wheat planting period (November–May), while drought severity during corn and rice planting seasons (mainly July–September) increased greatly within the western one-third of Afghan land.¹⁶ The far west border areas nearest Iran showed maximum changes in increasing drought severity.¹⁶ Part changes in rainfall regime were detected from 1951–2010 throughout Afghanistan such as small (<10%) decrease in average yearly rainfall over the west side of the country and less spring rains over all the regions. But these alterations are within the parameters of natural fluctuations and, hence, cannot definitively be associated with climate change.

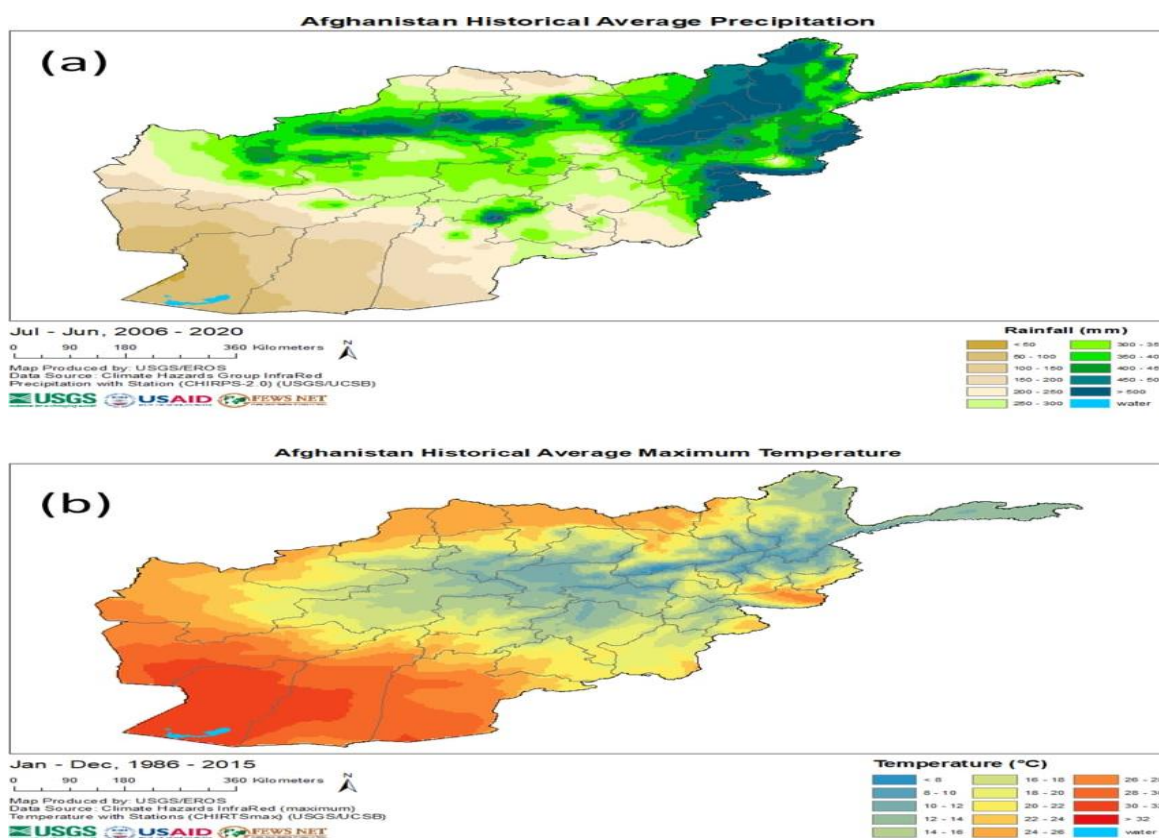


Figure 2: Historical Average Rainfall in Kabul City (1991–2020)

Source: Climate Change Knowledge Portal (World Bank); compiled by Authors' Study

Analysis of Precipitation Patterns in Kabul City (2006–2023)

The precipitation datasets for Kabul City utilized in the current study were derived from the Afghanistan Meteorological Department (AMD). A more precise long-term climate trend would ideally be provided by a consistent data set of at least thirty years. But because of decades of instability and civil war, most precipitation records were either incomplete or missing. It was only from 2005 that AMD started consecutively and reliably collecting precipitation data. Thus, this study examines the data from 2006 to 2023, an 18-year period.

Daily rainfall data were summed into annual totals for the investigation of yearly trends and variations. In order to see if rain has risen or fallen over the years, a linear regression model was utilized with the general equation:

$$y = ax + b \quad (1)$$

Where:

y = yearly precipitation (mm),

x = time series (year),

a = slope (trend), and

b = intercept (starting precipitation level).

The sign of the gradient (a) provides a direction for the trend:

$a > 0$ suggests an increasing trend,

$a < 0$ suggests a decreasing trend,

$a = 0$ suggests no significant change.

Also, standard deviation (σ) was determined to estimate the spread of annual precipitation from the average and to determine unusually dry or wet years within the study period. The mean annual rainfall in Kabul City during the period was about 306.87 mm, making the city an arid climate (areas with <400 mm/year).

Interannual variability was high as seen from the analysis of the rainfall data. The wettest year was 2009 with 385.6 mm of rainfall, whereas the driest year was 2008, registering a paltry 184.8 mm. The records also validated experienced drought episodes in 2007–2008 and 2016–2018 but revealed a moderate wet spell spanning between 2011 and 2014, as established by earlier research. While there was a slight upward trend in rainfall (~ 0.64 mm/year), it is too insignificant to reverse the impacts of fast urbanization, higher water demand, and rising temperatures.

Sl.NO	Year wise	Kabul city Rainfall in (MM)
1	2006	364.1
2	2007	264.8
3	2008	184.8
4	2009	385.6
5	2010	262
6	2011	325.8
7	2012	367.8
8	2013	369.1
9	2014	372.8
10	2015	319.9
11	2016	296
12	2017	240.7
13	2018	233.6
14	2019	367.8
15	2020	335.9
16	2021	229.67
17	2022	305.34
18	2023	297.9
19	Total Year wise Rainfall in (MM)	5523.61

Table 1: Annual Rainfall in Kabul City (2006–2023) [mm]

(Source: Afghanistan Meteorological Department; compiled by Authors' Study)

IV. Result and Discussion

An area that gets equal to or less than 400 mm of rainfall annually is classified as arid. According to the rainfall data recorded for Kabul City from 2006 to 2023, the average annual rainfall is around 306.87 mm, which validates that Kabul City falls in an arid climatic region. The cumulative precipitation during the 18-year study duration (2006–2023) totaled approximately 5,523.41 mm. As indicated in Figure 1, levels of rainfall varied immensely throughout this duration. The wettest year was 2009, with a total precipitation of 385.6 mm, whereas the driest year was 2008, which had only 184.8 mm of precipitation (both rain and snow). Other

somewhat high rainfall years are 2013 (369.1 mm), 2014 (372.8 mm), and 2012 and 2019 (both 367.8 mm). On the other hand, low rainfall years are 2021 (229.67 mm), 2018 (233.6 mm), and 2017 (240.7 mm). This fluctuation reflects the unpredictable and irregular pattern of precipitation in Kabul City, which can make urban planning, agriculture, and water resource management more difficult. The information underlines the necessity for sustainable planning policies and resilient infrastructure to avoid risks from both water scarcity and an unpredictable pattern of rainfall.

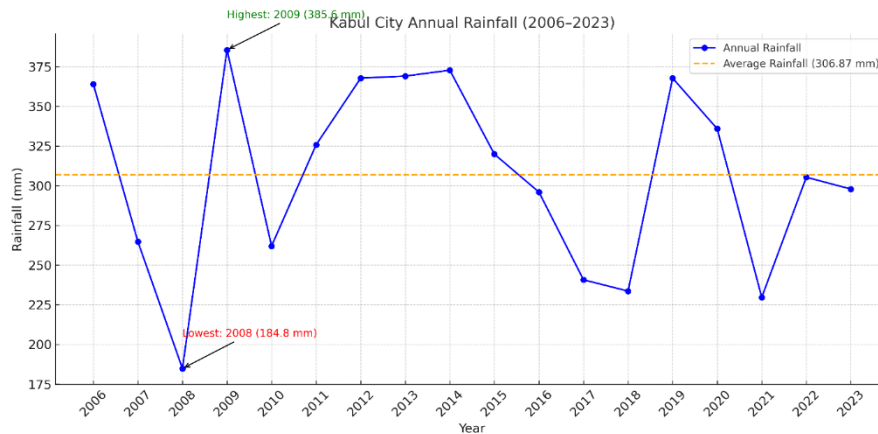


Figure 3: Annual Rainfall Precipitation in Kabul City (2006–2023) mm

Source: Afghanistan Meteorological Department; compiled by Authors' Study

Precipitation Analysis and Discussion for Kabul City

As shown in Graph 2, the annual average precipitation for Kabul City during the 18-year research duration (2006–2023) is 312.71 mm, validating Kabul's climate classification as arid, as areas receiving less than 400 mm/year are classified as so. The maximum rainfall for the study duration is 385.6 mm, and the minimum is 184.8 mm, reflecting great inter-annual variation in rainfall and the presence of both comparatively wet and extremely dry years. February accounts for around 19.32% (60.5 mm), March accounts for around 19.47% (61.6 mm), to the annual precipitation. They constitute the peak rainfall season, mainly because of winter storms and snow. From April to October, there is a clear drop in precipitation, to the lowest amounts in June and July: June: 3.6 mm (1.14%), July: 2.7 mm (0.86%). This is a dry season that overlaps with Kabul's summer season, with high evaporation and low rainfall, which enhances the possibility of drought. A minor peak in rain is seen in November (8.37%, 26.2 mm) and May (8.39%, 26.3 mm), which can be attributed to changing weather fronts and pre-monsoon activities. These results reaffirm the significance of seasonal water management measures, particularly for winter rain harvesting and summer drought suppression in the arid climate context of Kabul.

Month	Average Precipitation (mm)
Jan	34.51
Feb	60.5
Mar	61.6
Apr	56.2
May	26.3
Jun	3.6
Jul	2.7
Aug	9.3
Sep	3.5
Oct	10.3
Nov	26.2
Dec	18.8

Table 2: Average Monthly Rainfall in Kabul City (2006–2023) [mm]
(Source: Afghanistan Meteorological Department; compiled by Authors' Study)

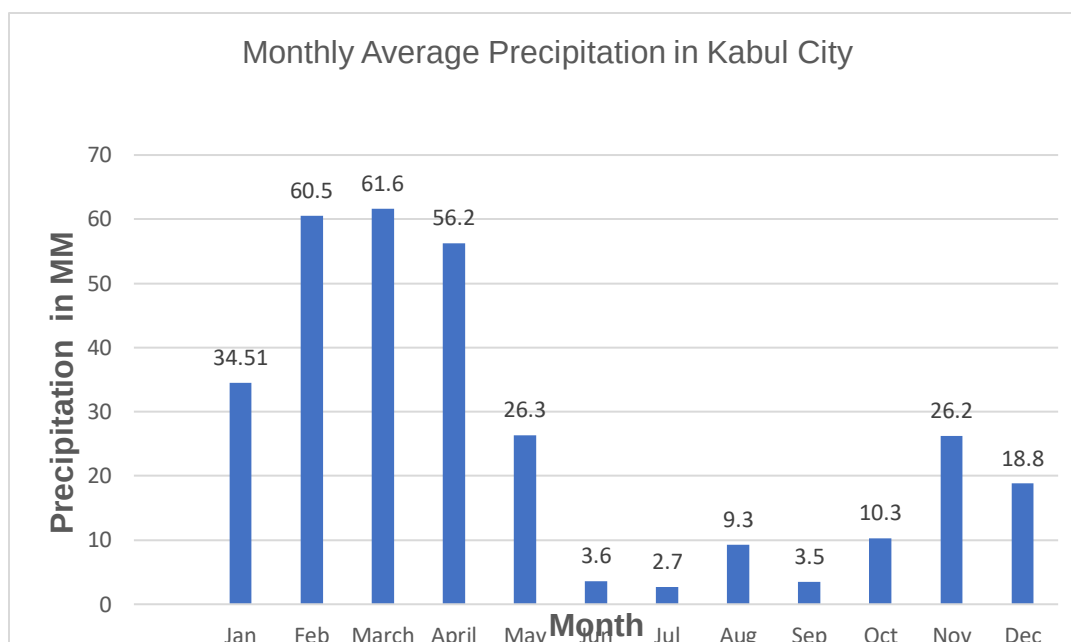


Figure 4: Average Monthly Precipitation in Kabul City (2006–2023) [mm]

Source: Afghanistan Meteorological Department; compiled by Authors' Study

Temperature Changes

One of the best indicators of climate change in Kabul is the increasing temperature. Several studies agree on a steep rise in mean temperatures in the last decades. [1] reports an increase in mean temperature above the global mean by 1.8°C from 1950 to 2010 in Afghanistan. The warming is expected to continue, at varying rates depending on carbon emissions. According to the Representative Concentration Pathway (RCP) 4.5 scenario, the expected increase in temperature is 1.7°C from 2006 to 2050 and 2.7°C from 2006 to 2099; under the RCP 8.5 scenario, the expected increase is 2.3°C and 6.4°C respectively. [1] Temperature rise is also reported by [2], which reports significant rise in temperature all over Afghanistan, though variations in precipitation are not as marked.

This warming trend has far-reaching implications for water resources, agriculture, and public health [1], [2]. [3] indicates that land surface temperature (LST) in Kabul province is on the rise from 1998 to 2022, with the maximum mean LST observed in urban areas, followed by bare soil and vegetation. This is a direct indication of urbanization being the cause of rising temperatures in the city. Another research paper on the effect of urbanization on the LST of Kabul and Jalalabad indicates that uncontrolled urbanization in Jalalabad results in higher LST than the planned city of Kabul [4]. The paper by [5] is a global study, indicating that mid to high latitude cities, e.g., dry climate zone cities, are the most likely to see the largest increase in hottest-month mean temperatures under high greenhouse gas emission scenarios. Though the research paper is not dedicated to Kabul, it gives a context to the global trend of climate change urban heat island effect.

Kabul is the capital of Afghanistan and is located in the east of the country, at a high elevation, 1,800 meters (5,900 feet) above sea level. Kabul has an arid continental climate, with cold winters and very hot, sunny summers. Winter is cold, with an average temperature of 1.5 °C (34.5 °F) in January, usually with nights below freezing. Occasionally, there is a cold snap, with lows of -15 °C (5 °F) or even lower. On January 1977, the temperature dropped to -20 °C (-4 °F). Snowfalls are quite frequent and sometimes heavy. Summer is hot, dry and sunny. In 2018, the temperature reached 40.5 °C (105 °F) in July and 41 °C (106 °F) in August.

Precipitation, quite limited, equals 300 mm (12 in) a year. The spring is the rainiest season. It nearly never rains during summer. In Kabul, the average of the coldest month (January) is that of 1.4 °C, of the warmest one (July) is that of 26.8 °C. Below are the average temperatures the sun is quite bright even in winter, and in summer, it often shines. Precipitation is equal to 12.2 inches per year: it is thus limited. It can range from 0.0 inches during the driest month (June) up to 2.8 inches during the wettest month (April). Below is the average precipitation.

Comprehending the climate change of Kabul City

Earth's climate is changing and global climate is to keep on changing over Kabul City Afghanistan and the world at large. The scale of climate change over the next several decades will be determined by the extent of greenhouse (heat-trapping) gases that have been put into the environment worldwide and by remaining uncertainty regarding Earth's climate sensitivity to them. With ambitious reductions in greenhouse gas (GHG) emissions, global mean temperature increase may be kept at 2°C or below. With no significant reductions in these emissions, increase in global yearly average temperatures relative to preindustrial times will reach nearly 5°C or higher by this century's end.

World climate keeps changing at a rapid pace relative to the pace of the natural cycles of climate that have occurred throughout Earth's history. Global average temperature trends, sea level rise, upper-ocean heat content, melting of land ice, arctic sea ice, seasonal permafrost thaw depth, and other climatic variables all show consistent evidence of a warming world. These trends are seen and verified by many, independent groups of scientists around the world. Global average temperature anomalies are shown in Figure 1; global average temperature has warmed by approximately 1°C since the 1880s.

Monthly Climatology of Average Minimum Surface Air Temperature, Average Mean Surface Air Temperature, Average Maximum Surface Air Temperature & Precipitation 1991-2020; Kabul, Afghanistan

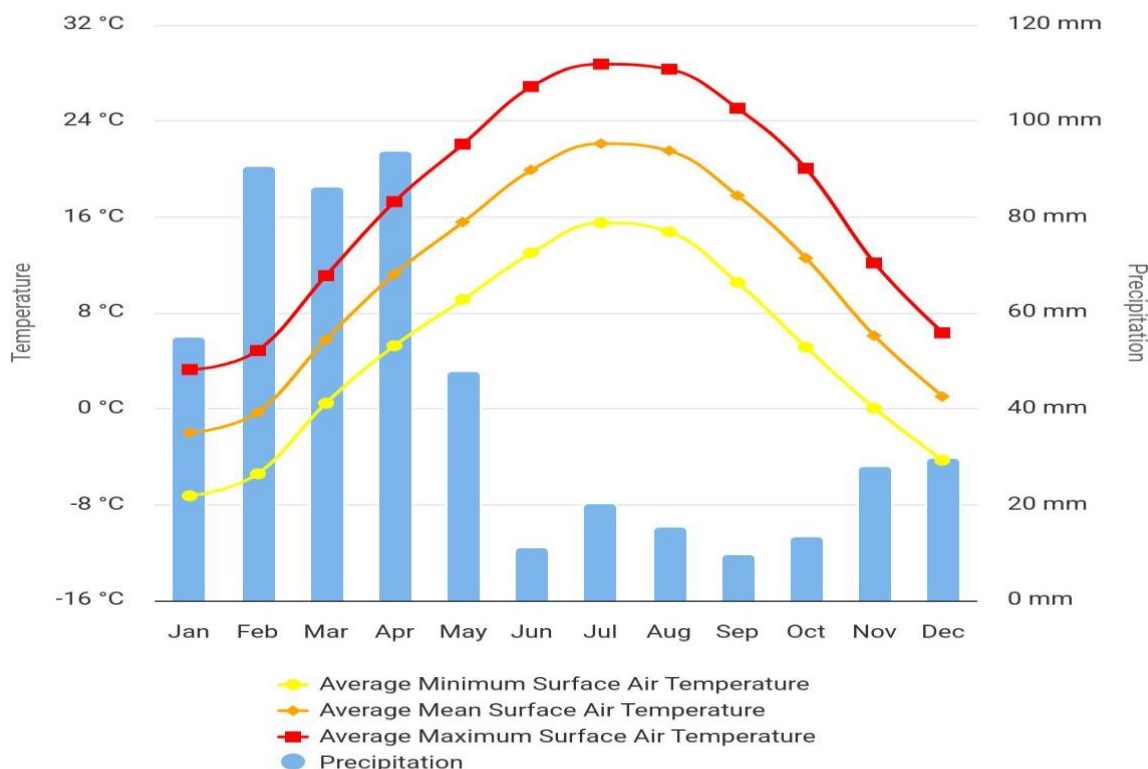


Figure 5: Monthly Climatology of Average Minimum, Mean, and Maximum Surface Air Temperature, and Precipitation in Kabul City (1991–2020)

Source: Climate Change Knowledge Portal (World Bank); compiled by Authors' Study

Afghanistan possesses a dry continental climate with significant temperature and precipitation fluctuation throughout the year. Temperatures also differ significantly by elevation, with mountainous areas having temperatures below zero on a yearly basis, but southern dry areas frequently having temperatures above 35°C. Precipitation is highly variable with topography, and the southwestern dry zone generally receives less than 150 millimeters (mm) per year of precipitation, whereas the northeastern mountain region receives more than 1,000 mm. Afghan conditions also exhibit intricate intra-annual interaction with big-scale climate processes, namely the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole. The latter is related to drought conditions over Afghanistan.

Natural Resources

The water situation of Afghanistan is complex. The country is dry, water deficient, and frequently drought-stricken, yet at the same time, it has access to considerable water resource based predominantly (80%) on runoff from mountains above 2,000 m.⁴⁷ The most notable rivers in terms of discharge volume are: the Amu Darya, bordering the northern edge of the country; the Helmand river (and larger drainage basin) in the south; and the Kabul/Kunar river system in the east. Analysis has indicated that Afghanistan has a number of rivers that are already regionally important in terms of their vulnerability in environmental, governance, economic, and social indicators. The Helmand River Basin is especially vulnerable, and concern is also raised about the Hari Rud and Amu Darya.⁴⁸ A number of common water management problems include siltation of reservoirs, absence of flow monitoring, and ineffective infrastructure maintenance and operation

Conventional water sources for people who reside farther away from rivers in Afghanistan are also susceptible to the effects of climate change. Karezes (hand-dug systems of tunnels) have traditionally been used to supply water to areas at the southern and western fringes of the Hindu Kush and Paropamisus mountains.⁵⁰ Many of these karezes, which access ground water via subsurface

canals, have dried up in the past two decades.⁵⁰ This reduction in water supply is likely to be compounded by projected temperature increases, via an accompanying reduction in snow cover at the sources of karezes.

The necessity for better management practices is evident, but the condition of the snow and glaciers that supply the rivers will also be of prime concern to the future prospects of Afghanistan's water resources. The analysis that is available indicates that the overall ice mass stored in the glacier systems, supplying Afghanistan's rivers is decreasing.⁴⁵ During the near-term (i.e. today through the 2050s) it is probable that runoff from major river systems will be sustained or even rise due to glacier melting. Depending on shifts in regional precipitation, glacier loss is expected to decrease runoff substantially in the longer-term. Runoff regime changes are also likely to evolve in coming decades as the smoothing impact of glacier melt decreases, and spring and early-summer peak runoff increases.⁵¹ Early spring snow melt, partly due to warming, has the potential to cause flash floods, eats snow in the higher mountains, changes flow rates as well as base flow, which affect groundwater. Research indicates a possible reduction in runoff from the Amu Darya of 10%–20% during the 2070s to the 2090s.⁵² These reductions, along with temperature, evaporation and CO₂-level changes, are likely to put heavy pressure on irrigation systems that will subsequently cause trans-boundary water management issues⁵³ and possibly crop production losses. These shifts, within the framework of continuous, fast, and poorly controlled development, put growing emphasis on planning, regulation and conservation of ecosystem services, such as forest cover, that stabilize water resources.

Impacts on Water Resources

The interaction of the altered temperature and precipitation trends has serious implications for Kabul's water supply. [6] directly attributes the lack of precipitation to a negative water balance, which results in water scarcity in Kabul City. The shortage is caused by the excessive groundwater consumption of the densely populated urban areas, car wash businesses, public bathhouses, and the recent development of greenhouses in the suburbs, according to the study. [6] [11] addresses the effects of climate change on Kabul sub-basins' water resources. The research finds variations in air temperature, precipitation, and surface and groundwater outflow from climate change from 1957 to 2017. The study finds increased discharge of the Panjshir River resulting from the melting of glaciers, indicating another effect of climate change on water supply in the area. [11] [1] points out that enhanced evapotranspiration is expected to intensify prevailing water stress, especially affecting agriculture. The research further points out that the length of the spring growing season (GSL) is expected to rise by approximately 20 days on average until 2050, which may present opportunities for longer agricultural husbandry or harvests if resources are properly managed. [1] [12] examines irrigation performance in the Kabul River Basin (KRB) for 2003–2013 based on equity, adequacy, and reliability of water delivery indicators. The research concludes that relative evapotranspiration (RET) is less than the target ($RET < 0.75$) for summer and winter seasons, which suggests poor water supply. The research also uncovers uneven water distribution across provinces and sub-basins, with maximum inequity being seen during early summer. The research identifies the inconsistent water distribution throughout the KRB, highlighting the importance of interventions for enhancing temporal and spatial water distribution of irrigation. [12] [13] simulates climate change effects on water yield and flood risk within transboundary Kabul basin. The model runs predict a 14% increase in mean annual precipitation and a 4.7°C temperature rise. River flows, however, are only expected to rise by 4%, mostly because of an augmentation of winter flows. In spite of this negligible increase in mean river flow, the model predicts a 37% augmentation of maximum flood inundation area and a 5–20 cm increase in flood depth. [13] This illustrates the disproportionate effect of climate change on flood events, even with relatively small changes in mean river flow. [14] examines the effect of climate change on flood frequency and intensity in the Kabul River Basin using bias-corrected downscaled climate models. The research predicts a rising trend in flood frequency and intensity due to more precipitation and warmer temperatures, which enhances glacier melting. Under projected future scenarios, the existing 50-year return period flood event is going to take place far more often. [14]

[15] particularly addresses the Panjshir catchment, examining the future development of snow cover and snowmelt within this catchment. The catchment lies in the north of Afghanistan and has warm-dry summers and cold-wet winters with high spatial and temporal heterogeneity of climate. The research identifies the essential contribution that snowmelt makes to servicing different sectors downstream and the livelihoods of tens of millions of people. [16] evaluates snow cover dynamics within western river basins of the Indus River system, including Afghan sub-basins, during 2001–2012. The authors identify a declining trend in snow cover in westerlies-influenced basins (upper basin, Astore, Hunza, Shigar, Shyok) and a rising trend in monsoon-influenced basins (Jhelum, Kabul, Swat, Gilgit). This points to the intricate and spatially heterogeneous effects of climate change on snow cover in the region. [17] employs the Snowmelt Runoff Model (SRM) to simulate daily discharge of the Salang River in northern Afghanistan during 2009–2011. The research proves the usability of the SRM to simulate river discharge in snow-fed mountainous basins and to evaluate the effect of climate change on river flow regimes. [17] [18] examines climate change effects on the flow regime of the transboundary Kabul River in the Hindu Kush basin, employing a snowmelt runoff model coupled with remote sensing snow cover data. The research forecasts a substantial rise in temperature and enhanced snowfall in the high-altitude areas of the basin, resulting in alterations in the flow regime and more intense and frequent flooding events. [18] The research emphasizes the necessity for coordinated approaches between riparian states to counter the projected effects. [18].

Land, Soil, and Biodiversity

During recent decades, Afghanistan has experienced widespread removal of its woodland and shrub cover (Figure 10). In combination with widespread overgrazing, such vegetation cover changes have enhanced soil erosion, land degradation, and loss of biodiversity.⁵⁵ Due to anticipated increases in temperature and drought, most of Afghanistan's ecosystems are anticipated to be

going through an ecological transition. Under more emissions-intensive pathways, areas in both the west and east of Afghanistan's Hindu Kush mountain range will be projected to transition from a sub-humid to semi-arid category. One probable outcome of climate-induced changes in ecozones will be a reconfiguration of the sustainable ranges for most plant and animal species. For a few, such as the snow leopard, there will be serious reduction of viable habitat.⁵⁶ For others, including the date palm tree, habitat lost in its traditional sites may be substituted by other, more northerly parts of the country.⁵⁷ Overall terms, changes are anticipated to be away from the equator (to the north) or upslope (to greater altitudes),⁵⁸ so the future of species already found on very high altitudes is at risk.

Impacts on Air Quality

Climate change also affects air quality in Kabul indirectly, reports the trend of rising air pollution in Kabul, especially seasonal pollution during winter as the requirement for heating goes up, resulting in more use of biomass and poor-quality fossil fuels. The higher usage of traditional resources leads to increased greenhouse gas (GHG) emissions and acts as a serious health risk to the public. [19] This research investigates the possibility of curbing GHG emissions by applying solar heating (SH) technology in residential houses. [20] examines long-term trends of tropospheric nitrogen dioxide (NO₂) columns over global large urban agglomerations such as Kabul. The research shows a sharp rise in NO₂ concentrations in Kabul, by 14.3% annually, from August 2002 to March 2012. [20] This indicates the sharp rise in air pollution in Kabul over this period. [21] investigates spatiotemporal variation of tropospheric NO₂ in South Asia based on 2004-2014 Ozone Monitoring Instrument (OMI) data. A decadal growth (14%) in NO₂ concentrations is noted by the study and associated with growth in motor vehicles, industries and agriculture, and biomass fuel burning. The paper also reports seasonal variability in NO₂, where spring and winter seasons experience higher levels. Kabul is listed as one of the most notable cities with increased concentrations of NO₂ (68%). [21] [22] briefly summarizes trends in South Asian air pollution during the COVID-19 lockdown. Though the research indicates a sharp drop in air pollution during the initial lockdown period of some South Asian megacities, such as Kabul, it also emphasizes ongoing efforts to cleanse the air after the lockdown phase is over. [22] [23] examines fine particulate matter (PM_{2.5}) concentration in different Pakistan cities, like Islamabad, Lahore, Peshawar, and Quetta. The research concludes that PM_{2.5} concentrations are higher than national air quality standards in all the cities throughout the research period (2007-2011). Back trajectory analysis shows that the pollution events in the cities are controlled by sources from western India and eastern Afghanistan. [23] [24] targets PM_{2.5} air pollution in Lahore, Pakistan, and concludes that PM_{2.5} concentrations are higher than national standards. Back trajectory analysis by the HYSPLIT model shows that PM_{2.5} pollution sources in Lahore are from regions within Afghanistan. [24]

Impacts on Public Health

The reported temperature, precipitation, and air quality changes have important public health implications for Kabul. [25] examines the spatiotemporal pattern of diarrheal disease in Afghanistan and its relation to climate factors. Aridity and mean daily temperature are found to be positively related, and average annual temperature is negatively related, to diarrhea occurrence. The research points to the crucial influence of climate on diarrheal trends and the importance of considering possible effects of climate change in public health analysis. [25] [26] performs a systematic review of the impact of climate factors on COVID-19 cases in various nations. Although the review emphasizes the variable and complex associations between meteorological factors and COVID-19, it indicates that temperature is an important factor in determining COVID-19 incidence in most countries. [26] The increase in temperatures and altered precipitation patterns enhance the risk of numerous health issues. Heat waves, compounded by the urban heat island effect, directly threaten human health, especially among vulnerable groups. Climate variations can influence waterborne disease propagation. Air pollution, as stated earlier, plays an important role in respiratory and cardiovascular diseases as well. [27] cites the effect of the urban heat island effect on the quality of life in cities of Africa in terms of morbidity, mortality, and conflicts. Although the research is not Kabul-specific, it highlights the need to take into account the UHI effect when planning cities and public health measures in fast-developing cities. [27] [28] reports on the spread of infectious diseases in Pakistan after the devastating 2022 floods, and how cascading impacts of climate disasters affect public health. The research highlights the difficulties of dealing with health emergencies following such incidents and the need for proper flood response and preparedness measures. [28]

Socioeconomic Impacts

Effects of climate change in Kabul are far-reaching and touch not only environment and health-related aspects but have far-reaching socioeconomic effects as well. [6] demonstrates water scarcity directly affects sectors such as agriculture, production of foodstuffs, and management of the water resource base. [29] estimates effects of socioeconomic change and climate variability on concentrations of *Escherichia coli* within the Pakistani Kabul River and demarcates interactive effects of anthropogenic and climatic variables with regard to governing water quality. The research focuses on the threats of waterborne disease in developing nations such as Pakistan because of poor waste treatment and manure management. [29] [30] examines the determinants of land use/cover change and cropland change in the Kabul River Basin. The research identifies that the expansion of cropland has favorable and unfavorable outcomes depending on landform, slope, soil depth, distance from the city, and climate. The research emphasizes the necessity of climate adaptation policies and measures to counteract the adverse effects of cropland expansion. [30] [31] examines the effects of land-use change on agricultural land in Kabul City. The research emphasizes the transformation of agricultural land into unplanned developments as a result of high population growth and poor enforcement of urban planning regulations. The research highlights the environmental and economic impacts of this change in land use and recommends supporting urban agriculture as a sustainable development strategy. [31] [32] discusses the sustainability of karezes (ancient water supply systems)

in Afghanistan under the new climate and population development conditions. The research proposes that karezes may not be sustainable in the face of prevailing trends, and therefore alternative water management strategies are required. [32] [33] reviews water resource development in northern Afghanistan and its consequences for the Amu Darya basin. The study points out the rise in water consumption for agriculture and the possible effects on the other consumers of the basin, such as the Aral Sea. The study underscores the significance of current cooperation among the bordering states and increased water management in the area. [33] [34] analyzes the problems and prospects of the energy sector in Afghanistan and its connection with transboundary water systems. The report identifies the poor rate of electrification in Afghanistan and the hindrances to the development of hydropower by virtue of transboundary water resource management challenges and security levels. [34] [35] examines poverty in several countries around the globe, including Afghanistan, and underscores the intricate connection between poverty and climate change. The report highlights a call for better education, infrastructure, health care, and governmental assistance to end poverty. [35] [36] gives an overview of Afghanistan's development opportunities and challenges, underlining the imperative to revitalize a failed state through better governance and sustainable resource management. [36] [37] writes about the security and development transition in Afghanistan beyond 2014, pointing to the difficulty of shifting from international military and civilian assistance. [37] [38] outlines the Afghan humanitarian crisis due to conflict with arms, drought, and human migration, with a focus on challenges and humanitarian relief opportunities. [38] [39] examines the influence of war, its effects, and drought on the surface land phenology of Afghanistan from space imagery. [39] [40] estimates biomass resources in Afghanistan as a viable alternative source of energy for Afghan development.

Research Gaps and Future Directions

In spite of the significant amount of research on climate change effects in Kabul, there are still some gaps in research. More precise, long-term, and high-resolution precipitation, temperature, and other climatic data are required to enhance the precision of climate projections and impact assessments. More research is required to further elucidate the intricate interactions among climate change, urbanization, and land use change, and their collective impacts on water resources, air quality, and public health. Enhanced methodologies for simulating the intricate hydrological processes in the region, especially those involving snowmelt and glacier dynamics, are also required. More research is needed to estimate the economic and social expense of climate change effects and to evaluate the effectiveness of different adaptation and mitigation policies. Incorporating socioeconomic aspects in climate change impact assessments is imperative for the establishment of effective and sustainable measures. Lastly, increased interdisciplinary research partnerships are necessary to tackle the intricacies and interconnectedness of challenges presented by climate change in Kabul. The current research offers a useful basis for future studies, emphasizing the need to fill these gaps to inform effective climate adaptation and mitigation policies in Kabul and other such areas.

V. Conclusion and Implications for Policy

The main indicators of climate change in Kabul City over the last 20 years have been studied in this study. These indicators include changes in humidity, rising temperatures, and rainfall variability, as well as their interrelated impacts on water resources, land use, air quality, public health, and socioeconomic systems. The findings show that Kabul is facing increasingly frequent droughts, generally rising average temperatures, and extremely erratic precipitation patterns, all of which exacerbate water scarcity and jeopardize urban resilience. The data suggests that climate change is a problem for Kabul City's development and governance in addition to being an environmental one. Kabul faces an existential threat from the combination of water scarcity, institutional fragility, and climate change. Kabul might become one of the first big cities to run out of water due to a combination of aquifer depletion and dwindling recharge from rainfall and snowfall. There would be disastrous effects for human security, stability, and public health. Within the next ten years, or perhaps sooner, Kabul will confront a humanitarian disaster unless significant reforms are made. A multifaceted, proactive approach is essential and not optional. Together with strong administration, efficient demand management, and empowered communities, the Panjshir Pipeline and Shahtoot Dam must act as the cornerstones. Above all, securing water is essential for Kabul's survival, resilience, and long-term growth. This requires both consistent foreign assistance and political commitment at the national level. Implications for policy are crucial. First, the results highlight how urgently integrated water resource management is needed to balance urban use with scarce and fluctuating supply. Resilience will require investments in sustainable infrastructure, such as urban green spaces, enhanced irrigation efficiency, and rainwater collection. Second, the connection between urbanization and increasing land surface temperatures necessitates the extension of climate-sensitive land use plans, the adoption of energy-efficient housing, and the tighter enforcement of urban planning laws. Third, the effects of climate change on air quality and public health call for improved environmental health monitoring systems, as well as increased use of renewable energy sources and less dependence on low-grade fossil fuels and biomass. Afghanistan's obligations under the Paris Agreement and the necessity of advancing Nationally Determined Contributions (NDCs) for climate adaptation and mitigation are precisely in line with the findings on a global scale. Additionally, they help achieve Sustainable Development Goal 13 (Climate Action) by offering localized data to help design adaptation measures. Furthermore, by incorporating climate risk assessments into city design, Afghanistan is better able to comply with the Sendai Framework for Disaster Risk Reduction, especially when it comes to lessening the susceptibility of Kabul's quickly expanding population to heat waves, droughts, and floods. In conclusion, addressing climate change in Kabul City demands both local adaptation measures and global cooperation. Strengthening governance, expanding scientific data collection, and fostering community-based resilience strategies will be pivotal for ensuring that Kabul not only survives but adapts and thrives under the pressures of a changing climate.

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