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Exploring Climate Variability in Lahore, Pakistan: Investigating the Interplay of Precipitation, Relative Humidity, and Temperature

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In recent years, the rapid changes in climate parameters such as temperature, precipitation, and relative humidity have become increasingly evident. To address this, the study investigates the intricate fluctuations within distinct climatic parameters precipitation, relative humidity, and maximum temperature—for ten years that capture pronounced pre-2020 climatic variability and provides a critical baseline for interpreting more recent and ongoing climatic shifts in Lahore. Understanding these dynamics is important due to Lahore's vulnerability to climate variation and its implications for agriculture and urban sustainability. Monthly climatic data was investigated to identify trends, while linear regression and correlation analyses were employed to quantify relationships among the variables. Findings revealed that precipitation shows a consistent pattern of minor fluctuations across the years. Of particular note, 2015 emerges as the driest year among the dataset, while 2013 and 2017 stand out as the wettest years. The years 2010 and 2014 observed the highest levels of precipitation. Relative humidity, uncovers a remarkable uniformity in its yearly evolution from 2010 to 2019 having lowest values during the summer months, primarily in May and peak values during the winter months, specifically in January and February. The analysis of maximum temperature patterns, except for 2014, showcases a consistent pattern of uniformity from 2010 to 2019. May consistently records the highest maximum temperatures, while January consistently registers the lowest minimum temperatures. Quantitative analysis demonstrated a strong inverse relationship between maximum temperature and relative humidity, with correlation coefficients ranging from −0.43 to −0.71 and regression coefficients varying from −0.40 to −0.84. Similarly, temperature and precipitation exhibited weak to moderate negative correlations (CRC = −0.14 to −0.32), indicating reduced precipitation under warmer conditions. In contrast, precipitation and relative humidity showed positive associations with correlation coefficients ranging from 0.10 to 0.26 and regression coefficients reaching 0.70, suggesting that increased precipitation contributes to elevated humidity levels. These findings highlight the strong relation among climatic variables and underscore their relevance for agricultural planning, water resource management, and urban climate adaptation strategies particularly in light of intensifying climate variability observed in the post-2019 period.

Keywords: Climate, Temperature, Precipitation, Relative Humidity, Linear Regression Coefficient, Correlation Coefficient

Introduction:

The global climate system has undergone substantial changes in recent decades due to the continuous increase in greenhouse gas concentrations in the atmosphere. These emissions, primarily driven by urbanization, industrialization, and fossil fuel combustion, have significantly altered the Earth's energy balance, leading to global warming and associated shifts in hydro-meteorological variables such as temperature, precipitation, and humidity [1][2][3]. The consequences of this warming include increased frequency and intensity of extreme weather events, including heatwaves, floods, droughts, and cyclones, which have been widely documented across different regions of the world [4][5][6].

Recent climate science literature (2021–2025) highlights that climate change impacts are no longer limited to long-term warming trends but are increasingly expressed through heightened climate variability and extremes at regional and local scales [7][8]. Ranging from 1.3°C to 4.4°C over the 21st century, with increasing implications for agricultural systems, water resources, and urban sustainability [9]. In parallel, studies emphasize that changes in atmospheric temperature are strongly linked with shifts in precipitation patterns and humidity dynamics, reflecting the interconnected nature of climatic variables within the hydrological cycle.

In South Asia, and particularly in Pakistan, climate change poses a severe challenge due to its high vulnerability ranking in the Global Climate Risk Index. Long-term observations indicate significant variability in temperature and precipitation patterns, with increasing evidence of climate-induced stress on agriculture and water resources [10][11]. For example, rainfall variability has been shown to significantly affect urban resilience, as demonstrated by extreme monsoon rainfall events in Karachi that caused severe flooding and infrastructure disruption [12]. Similarly, long-term temperature analyses in Lahore have revealed complex temporal variability in maximum and minimum temperatures, highlighting the non-linear nature of climate change signals in the region [13].

Precipitation trends show strong spatial and temporal variability across global and regional scales. While some regions such as parts of Europe have experienced increasing precipitation and extreme rainfall events [14], South Asia exhibits mixed patterns, including both increasing and decreasing seasonal rainfall trends depending on the basin and period of analysis [15].In Pakistan, studies have reported long-term increases in rainfall variability from 1901 to 2008 [16], emphasizing the need for localized climate assessments.

In addition to temperature and precipitation, relative humidity plays a critical but often underexplored role in climate system dynamics. As water vapor is the most influential greenhouse gas, it acts as a key feedback mechanism that amplifies warming effects by regulating atmospheric moisture and precipitation processes. Rising global temperatures enhance the atmosphere's moisture-holding capacity, leading to alterations in humidity distribution and precipitation patterns [17][18]. However, despite its importance, fewer studies have systematically examined long-term interactions between relative humidity and other climatic variables at local scales.

Pakistan's economy is highly dependent on agriculture, which contributes significantly to national GDP and livelihood security. Given that rainfall is a primary water source for agriculture and livestock, variability in precipitation and associated climatic parameters poses serious risks to food security and agricultural productivity [19][20]. Therefore, understanding the coupled behavior of temperature, precipitation, and relative humidity is essential for assessing climate variability impacts in agricultural regions.

Despite extensive global and regional studies, a key gap remains in the integrated assessment of long-term interactions among temperature, precipitation, and relative humidity at the city scale in Pakistan, particularly using combined regression and correlation frameworks over extended periods. Lahore, being one of the most climate-vulnerable urban centers, requires detailed evaluation of these interrelationships to support effective adaptation and planning strategies. This study addresses this gap by analyzing multi-decadal climatic variability and quantifying the statistical relationships among key climatic variables to better understand local-scale climate dynamics.

Research Gap and Novelty of the Study:

Recent studies have extensively investigated individual climatic variables, including temperature trends, precipitation variability, and relative humidity changes at global and regional scales [3][17]. In Pakistan, several studies have examined rainfall variability, temperature dynamics, and climate-related impacts on agriculture and urban environments [16][11][12][13]. However, limited attention has been given to an integrated assessment of the statistical interrelationships among maximum temperature, precipitation, and relative humidity at the city scale, particularly for Lahore.

Most previous studies have focused on trend detection, climate projections, drought assessment, precipitation forecasting, or single-variable analyses [21][10][22], whereas comparatively fewer studies have quantified the coupled behavior of climatic variables using regression and correlation approaches over extended observational periods. Therefore, a knowledge gap remains in understanding how temperature, precipitation, and relative humidity interact and influence each other under local climatic conditions in Lahore.

The novelty of the present study lies in integrating regression and correlation analyses to quantify the interactions among these climatic variables using long-term monthly observations for Lahore. This approach enables identification of both the direction and magnitude of climatic associations and provides localized evidence for understanding climate variability and supporting adaptation strategies in urban and agricultural sectors.

Objectives of the study:

The main objective of this study is to examine the long-term variability and trends in key climatic parameters, with temperature, precipitation, and relative humidity, over the selected study region. The study further aims to analyze seasonal and interannual variations and assess the occurrence of extreme climate events under changing climatic conditions. Moreover, the research seeks to deliver scientifically robust insights that can support climate risk assessment, agricultural planning, and climate change adaptation policies.

Methodology:

Area of study:

Lahore, a prominent and populous city in Pakistan, holds the status of being a significant urban center following Karachi. Serving as the capital of the Punjab province, Lahore is geographically situated between 31°15' to 31°45'N and 70°01' to 74°45'E. Map of Lahore is shown in Figure 1. The city's borders are defined by the Sheikhupura district to the north and west, Wagah to the east, and district Kasur to the south. The Ravi River courses along its northern boundary. The land area encompassed by Lahore currently spans 1019 square kilometers, with ongoing expansion. The city experiences four distinct seasons: winter (January-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-December). Notably, June emerges as the hottest month, with average high temperatures consistently surpassing 40°C (104°F).

Figure 1. Map of Lahore

Data sources:

Data of temperature and relative humidity has been downloaded from underground (https://www.wunderground.com/), which provided free access to the data of Allama Iqbal international airport, Lahore. Precipitation data has been downloaded from NASA website Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/).

Figure 2. Methodological Workflow of the Study

Description of Methodological Workflow:

The study follows a structured multi-step workflow to analyze climatic variability in Lahore from 2010 to 2019 as shown in figure 2. The process begins with **data collection**, where daily temperature and relative humidity data were obtained from Weather Underground (Allama Iqbal International Airport, Lahore), while precipitation data were acquired from NASA Giovanni satellite-based datasets.

The second stage involves data processing and preprocessing, where raw daily observations were checked for completeness and consistency. Prior to analysis, all datasets were subjected to basic quality control procedures, including range checking to remove physically unrealistic values and consistency checks to identify abnormal spikes or recording errors.

Missing data were minimal and occurred sporadically due to observational or instrumental limitations. These gaps were addressed using linear interpolation at the daily scale prior to monthly aggregation, ensuring temporal continuity of the dataset. The proportion of missing values was negligible and did not exceed a minor fraction of the total dataset, thereby ensuring robustness of the time series.

The third stage includes trend analysis, where temporal patterns in each climatic variable were examined to identify interannual variability, seasonal fluctuations, wet and dry years for precipitation, and monthly extremes for temperature and relative humidity.

The fourth stage involves statistical analysis, where linear regression was applied to quantify the relationships among maximum temperature, precipitation, and relative humidity. This analysis was used to determine both the strength and direction of climatic interactions over the study period. The primary objective of this study is to quantify the strength and direction of relationships among climatic variables (maximum temperature, precipitation, and relative humidity) at a monthly scale over a relatively short observational period (2010–2019). Linear regression and correlation analysis are well-suited for this purpose as they provide direct, interpretable measures of association and allow comparison of inter-variable dependencies.

In contrast, non-parametric trend tests such as the Mann-Kendall test and Sen's slope are primarily designed for detecting monotonic trends in long-term datasets rather than examining inter-variable relationships. Similarly, time-series decomposition methods are more appropriate for separating seasonal, trend, and residual components in longer and higher-resolution datasets. Given the focus of this study on interdependence and climatic coupling rather than long-term monotonic trend estimation or forecasting, linear regression and correlation analysis were deemed the most appropriate and interpretable methods.

The final stage consists of interpretation of results, where statistical outputs were evaluated in the context of regional climate variability, with emphasis on identifying physical relationships among climatic variables and their implications for environmental and agricultural systems in Lahore.

Linear regression analysis:

Linear regression analysis was used to measure the direction and magnitude of trends in precipitation, relative humidity, and maximum temperature over the study period. Linear regression was nominated due to its simplicity, robustness, and widespread use in climate trend detection, permitting straightforward interpretation.

Results and Discussions:

Precipitation:

Precipitation holds immense significance as a crucial natural climate parameter, particularly for Pakistan, an agrarian nation where agriculture serves as a pivotal pillar of the economy. The agricultural sector's role is paramount in shaping Pakistan's economic landscape. Illustrated in Figure 3, the precipitation trends in Lahore over the past decade underscore noteworthy patterns. A consistent increase in precipitation during the peak monsoon months of July and August across all years, highlighting the dominant influence of the South Asian monsoon system on regional rainfall patterns. Interannually, notable distinctions emerge, with the years 2010 and 2014 recording the highest precipitation values, signifying periods of enhanced monsoonal activity. Notably, there's an observed consistent rise in precipitation rates during the months of July and August each year. The years 2010 and 2014 stand out with the highest recorded levels of precipitation. Conversely, 2015 emerges as the driest year within this timeframe, marked by a notably low mean value. Conversely, the years 2011, 2013, 2014, and 2019 experience heightened precipitation, signifying them as the wettest years (as depicted in Figure 3 and detailed in Table 1).

Quantitatively, the mean annual precipitation during the study period was 1.88 mm, with an interannual standard deviation of ±0.47 mm, indicating moderate to high variability in precipitation across years. The coefficient of variation (CV = 24.97%) further confirms substantial rainfall fluctuations during the study period. The maximum annual precipitation was recorded in 2013 (2.61 mm), followed closely by 2014 (2.50 mm), exceeding the long-term mean by approximately 38.6% and 32.8%, respectively, reflecting intensified monsoonal activity during these years. In contrast, 2015 represents the driest year with a minimum annual precipitation of 1.16 mm, which was substantially lower than the climatological average.

Interannual comparison further indicates that 2011, 2013, 2014, and 2019 experienced above-average precipitation conditions, whereas 2012, 2015, 2016, 2017, and 2018 remained below the long-term mean. These quantitative findings support the visual interpretation shown in Figure 3 and strengthen the assessment of precipitation variability in Lahore.

The observed precipitation variability in Lahore is consistent with previous rainfall assessments in Pakistan, which reported substantial spatial and temporal heterogeneity in rainfall patterns and identified inter-decadal shifts in Punjab. However, unlike the broader provincial declining tendency, Lahore exhibited pronounced interannual variability with wetter and drier periods, highlighting the influence of local monsoonal dynamics and regional climatic conditions [23].

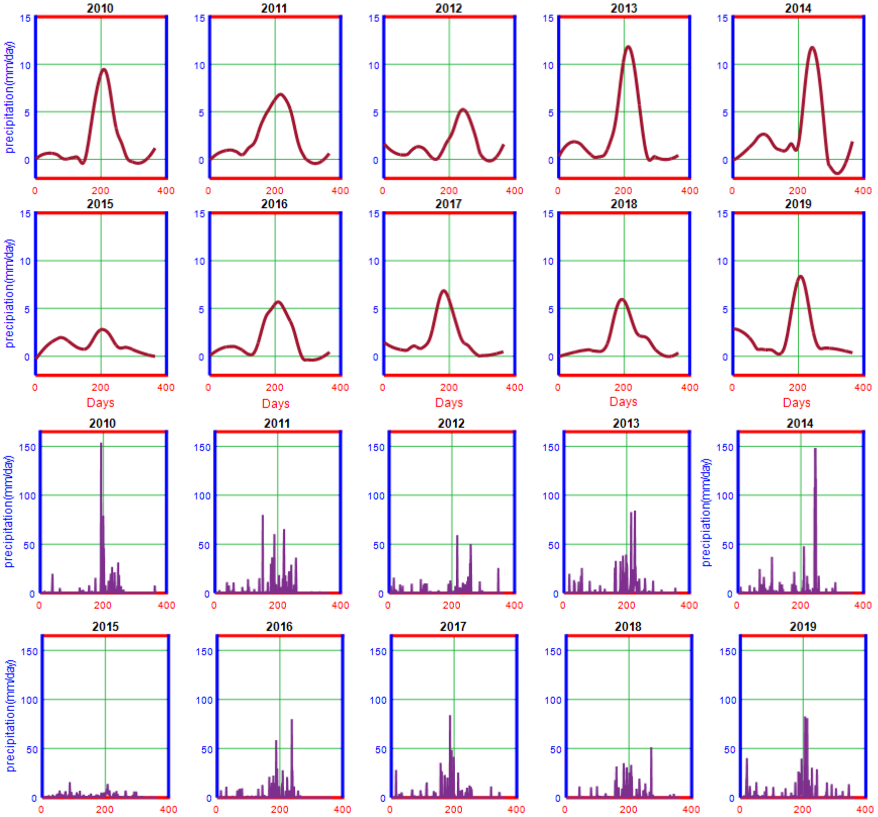

Figure 3. Daily variation of precipitation from 2009 to 2019 original data (row 1:2) and smooth data (row 3:4)

Table 1. mean, median, mode and standard deviation (Std) of precipitation data.

Years	mean	Std	Years	mean	Std
2010	1.860	10.0870	2015	1.1604	1.9557
2011	2.1427	8.1787	2016	1.6037	6.4782
2012	1.4685	5.4141	2017	1.7668	6.8877
2013	2.6116	8.9680	2018	1.5273	5.5426
2014	2.5021	13.1633	2019	2.1931	7.8924

Relative Humidity:

Relative humidity represents the ratio of moisture present in the air to the maximum amount of moisture the air can hold. This parameter is typically measured using a hygrometer, an instrument designed for this purpose. Figure 4 visually portrays the fluctuations in relative humidity within Lahore over the preceding decade (2010 to 2019) and detailed in Table 2. The results show an outstanding consistency in the seasonal pattern of relative humidity across all years, giving a stable climatic control over atmospheric moisture conditions in the region. In general, the lowest relative humidity values are observed during May, a trend consistent across all years except for 2014, where May stands as the driest month. The analysis reveals a recurring pattern: the air holds less moisture during the summer months compared to the winter months. This is most evident by observing Figure 4, which demonstrates that relative humidity experiences a decline from January through June, followed by a subsequent increase during the monsoon season owing to precipitation events. Such variations in relative humidity are critical, as they directly affect thermal comfort, crop water demand, and the formation of precipitation, thereby playing a key role in local climate dynamics and agricultural sustainability in Lahore.

Quantitatively, the mean annual relative humidity during the study period was 81.36%, with an interannual standard deviation of ±1.68%, indicating relatively low variability across years. The coefficient of variation (CV = 2.06%) further confirms that relative humidity remained comparatively stable throughout the study period. The maximum annual mean relative humidity was recorded in 2015 (83.28%), exceeding the long-term mean by approximately 2.35%, indicating comparatively more humid atmospheric conditions during that year. In contrast, the minimum annual mean relative humidity was observed in 2012 (78.50%), which was approximately 3.51% below the climatological average. The overall range of annual mean relative humidity was 4.78%, reflecting limited interannual fluctuation.

Interannual comparison further shows that 2011, 2013, 2014, and 2015 exhibited above-average relative humidity conditions, while 2010, 2012, 2016, 2017, 2018, and 2019 remained close to or below the long-term mean. These quantitative results strengthen the visual interpretation and provide a more comprehensive comparison of relative humidity variations across years.

The seasonal behavior of relative humidity observed in Lahore aligns with recent studies conducted in Pakistan that identified RH as a key indicator of atmospheric moisture variability and regional drought conditions. The gradual decline before the monsoon and recovery during wetter months reflects broader humidity–precipitation interactions reported across different climatic zones in Pakistan [24].

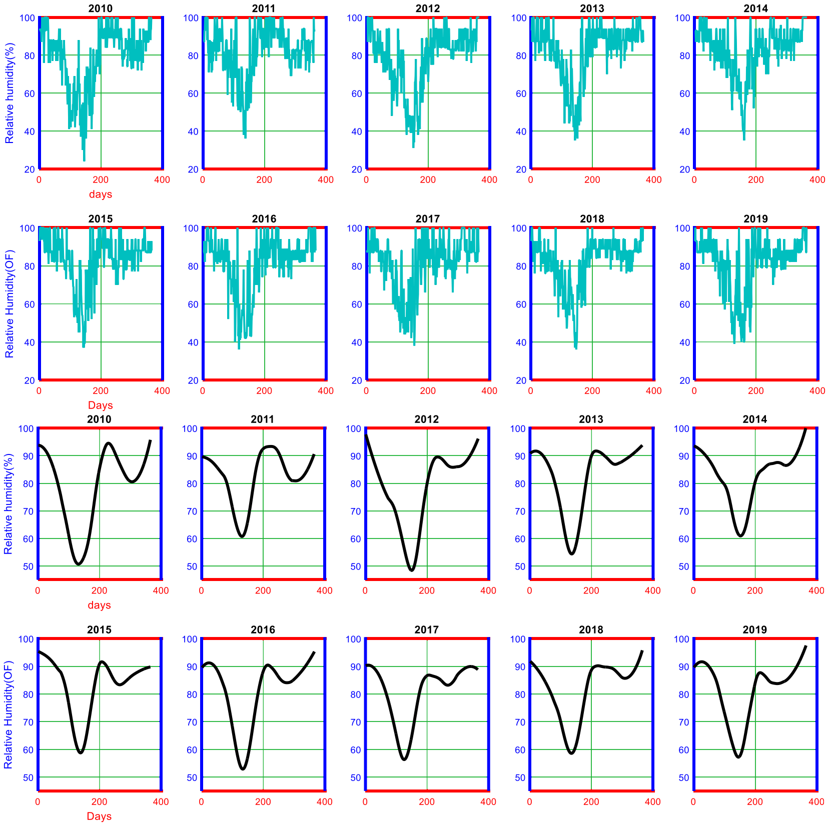

Figure 4 Variation of Relative Humidity from 2009 to 2018 (a) original (b) smooth

Table 2. Mean, median, mode and standard deviation (std) of relative humidity.

Years	Mean	Median	Mode	Std	Years	Mean	Median	Mode	Std
2010	78.7123	83	94	16.3892	2015	83.2767	87	88	13.2863

2011	82.4055	84	94	13.0674	2016	81.2077	84	88	14.7647
2012	78.5000	83	94	16.0078	2017	80.9205	84	87	13.9123
2013	82.5178	87	94	14.4792	2018	81.8301	87	89	12.7535
2014	82.7452	87	88	12.8702	2019	81.4493	84	88	14.1955

Maximum Temperature:

Displayed in Figure 5 is the representation of the variation pattern in maximum temperatures within Lahore over the preceding decade, encompassing the years 2010 to 2019 and detailed in Table 3. The observed trend in maximum temperature fluctuations remains largely consistent throughout the duration of the study, with the exception of the year 2014. Typically, there's an initial upward trajectory in maximum temperatures, leading to their zenith, frequently observed in the month of May. The peak in May can also be credited to intense solar radiation, clear-sky conditions, and pre-monsoon heat growth. Subsequently, a decline in temperatures ensures post-peak. The primary driver for this temperature decrease is the advent of rain subsequent to May. This aligns with the initiation of the monsoon season, usually taking effect during these months. After the monsoon season concludes, there's a discernible shift: maximum temperatures begin ascending until September, at which juncture they start to recede once more. The inconsistent behavior observed in 2014 may be related to early monsoon activity or increased cloud cover that suppressed extreme heating. These temperature distinctions also mirror strong relations between rainfall, humidity, and surface energy balance, with important consequences for heat stress and agricultural activities in Lahore.

Although the present study is limited to the 2009–2019 period, recent studies have reported continued warming trends and increasing urban thermal stress across Lahore and surrounding regions, providing an important context for interpreting post-2019 climatic variability. In particular, rapid urban expansion and land-use changes have been associated with increasing land surface temperature and intensified urban heat island effects, which may contribute to seasonal temperature anomalies and modify local climatic conditions in the region [25][26][27]. In Pakistan, climate change increasingly manifests through extreme summer monsoon precipitation and subsequent flooding, with recent studies using Intensity–Duration–Frequency (IDF) and Quantile–Duration–Frequency (QDF) frameworks based on ERA5 precipitation and long-term streamflow records (1950–2024) demonstrating increasing flood probability associated with monsoon extremes [28].

Quantitatively, the mean annual temperature during the study period was 86.47, with an interannual standard deviation of ±1.04, indicating relatively low year-to-year variability in temperature conditions. The coefficient of variation (CV = 1.20%) further demonstrates that temperature remained comparatively stable throughout the study period. The maximum annual mean temperature was recorded in 2010 (88.25), exceeding the long-term mean by approximately 2.06%, indicating relatively warmer conditions during that year. In contrast, the minimum annual mean temperature was observed in 2019 (85.00), approximately 1.70% below the long-term average. The overall range of annual mean temperature was 3.25, reflecting limited interannual fluctuation.

Interannual comparison shows that 2010, 2011, 2012, 2016, and 2017 experienced above-average temperature conditions, whereas 2013, 2014, 2015, 2018, and 2019 remained below the long-term mean. These quantitative statistics strengthen the interpretation of Figure 3 by providing numerical evidence of temporal temperature variability across the study period. The temperature behavior observed in the present study is consistent with our previously published work on extreme temperature trends in Lahore [13], which reported noticeable temporal variability in annual and seasonal temperature conditions. Similar to the earlier findings, the current analysis indicates that temperature changes in Lahore are influenced by regional climatic variability and local environmental factors rather than a uniform long-term pattern.

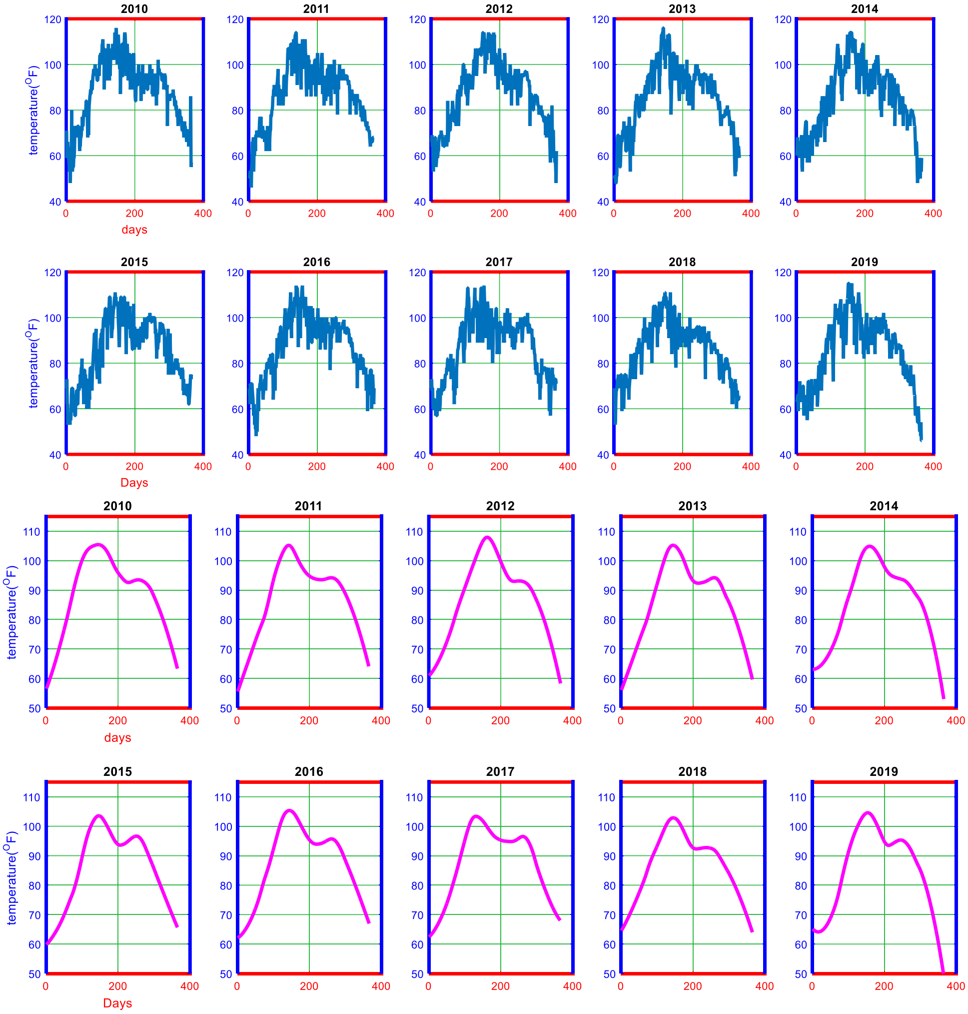

Figure 5. Maximum Temperature variation from 2009 to 2018 (a) original (b) smooth

Table 3. Mean, median, mode and standard deviation (std) of temperature.

Years	Mean	Median	mode	Std	Years	Mean	median	Mode	Std
2010	88.2466	91	96	14.4424	2015	85.6712	89	100	14.2793
2011	86.8466	89	95	14.1267	2016	87.3962	91	96	13.8785
2012	86.7077	89	95	14.8425	2017	87.2521	91	96	13.7861
2013	85.8438	87	95	14.6034	2018	86.5452	89	95	12.0945
2014	85.2301	87	95	15.2208	2019	85	88	88	15.5754

Relationship of maximum temperature and precipitation:

Temperature and precipitation exhibit a strong interdependence, particularly evident during the summer months and following May, which marks the onset of the monsoon season. This heightened precipitation is depicted in Figure 6. The surge in rainfall can be attributed to the rapid escalation of temperatures during the months of March, April, and May, collectively known as the pre-monsoon period. Elevated temperatures foster a greater capacity for warm air to absorb additional water molecules, subsequently propelling this moisture-laden air upwards. This process is pivotal in triggering precipitation events during the monsoon season. Conversely, within the monsoon period, there's a noticeable decline in the maximum temperature, attributable to the occurrence of rain, as illustrated in Figure 6 and Table 4. Correlation coefficients (CRC) and linear regression coefficients (LRC1, LRC2) between maximum temperature, relative humidity, and precipitation. CRC values designate the strength and direction of the relationship (positive values specify direct correlation, negative values designate inverse correlation). LRC1 and LRC2 show the slope of linear regression lines for individual variable pairs, giving the rate of change of one variable with respect to another. These metrics help to measure how temperature, humidity, and precipitation relate seasonally and annually. The abundant rainfall, or precipitation, significantly contributes to the cooling effect observed in maximum temperatures. This intricate relationship between temperature and precipitation is particularly pronounced during the summer months, as showcased in Figure 6. To quantify this relationship, various correlation coefficients have been computed, revealing a negative coefficient that underscores an inverse relationship between maximum temperature and precipitation during the summer. This interaction also explores the role of latent heat exchange during condensation, which reorganizes atmospheric energy and moderates surface temperatures. Interannual changes propose that years with more monsoon intensity exhibit a more distinct reduction in post-May maximum temperatures. Such sensitivity of temperature–precipitation coupling has important consequences under climate change, where different monsoon dynamics may intensify or disrupt this recognized inverse relationship.

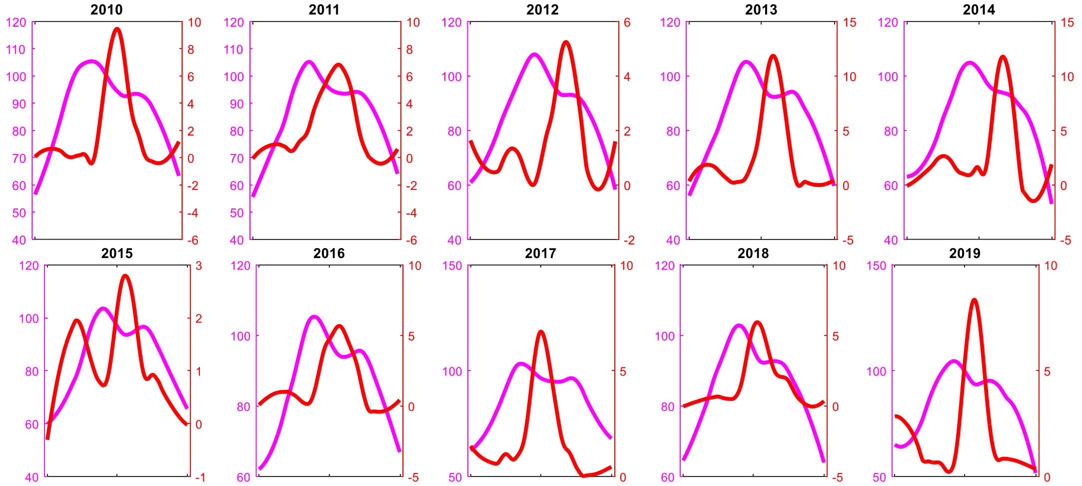

Figure 6. Relation of maximum temperature and precipitation (red curve represents precipitation and magenta curve represents temperature)

Table 4. LRC1 (Linear regression coefficient when the temperature is independent while precipitation is the dependent variable), LRC2 (Linear regression coefficient when the temperature is dependent while precipitation is independent variable) and CRC (correlation coefficient).

Years	LRC1	LRC2	CRC	Years	LCR1	LCR2	CRC
2010	-0.4151	-0.1139	-0.2174	2015	-0.0763	-1.017	-0.2786
2017	-0.3962	-0.1847	-0.2705	2016	-0.4184	-0.2426	-0.3185
2012	-0.2759	-0.3192	-0.2968	2017	-0.1853	-0.101	-0.1368
2013	-0.449	-0.1823	-0.2861	2018	-0.2133	-0.1771	-0.1944
2014	-0.6735	-0.1415	-0.3087	2019	-0.3168	-0.1773	-0.2370

Relationship of maximum temperature and relative Humidity:

Temperature and relative humidity are closely intertwined, with an evident inverse correlation between the two variables. This inverse relationship stems from the fact that when temperatures reach their peak, relative humidity tends to be at its lowest. This occurrence is a result of warm air's reduced capacity to hold moisture compared to cold air. Notably, during the monsoon season, relative humidity tends to be high due to the cooling effect associated with precipitation, as portrayed in Figure 7. Table 5 provides a comprehensive overview of various correlation coefficients computed for maximum temperature and relative humidity These coefficients substantiate the inverse relationship between these variables. This is indicated by the negative values of the coefficients, which signify the presence of an inversely proportional association between maximum temperature and relative humidity. This pattern reflects basic thermodynamic principles, where rising temperatures elevate the saturation vapor pressure, thereby lowering relative humidity when moisture supply is restricted. The strengthened inverse relationship during pre-monsoon months signifies the governance of temperature-driven atmospheric drying. In distinction, monsoon rainfall increases moisture availability, momentarily weakening this inverse association by elevating relative humidity despite restrained temperatures.

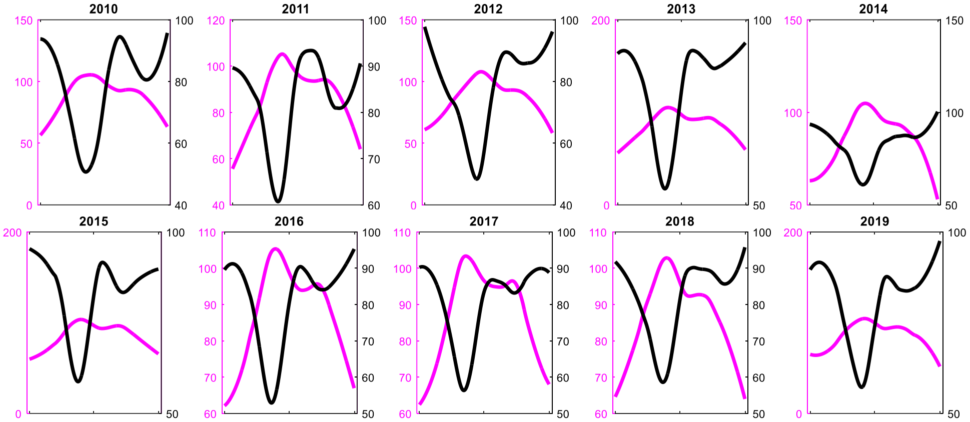

Figure 7. Relation of maximum temperature and relative humidity (magenta curve represents temperature and black curve represents Relative humidity)

Table 5. LRC1 (Linear regression coefficient when the temperature is independent while relative humidity is the dependent variable), LCR2 (Linear regression coefficient when the temperature is dependent while relative humidity is independent variable), CRC (correlation coefficient)

Years	LCR1	LCR2	CRC	Years	LCR1	LCR2	CRC
2010	-0.7388	-0.5737	-0.6510	2015	-0.5991	-0.692	-0.6438
2011	-0.4016	-0.4693	-0.4341	2016	-0.6631	-0.5859	-0.6232
2012	-0.6984	-0.6004	-0.6475	2017	-0.6343	-0.6228	-0.6285
2013	-0.6275	-0.6383	-0.6329	2018	-0.6508	-0.5853	-0.6171
2014	-0.6028	-0.8431	-0.7129	2019	-0.629	-0.7572	-0.6901

Relationship of precipitation and relative humidity:

The behavior of precipitation and humidity exhibits striking similarities in figure 8. During summer, both reach their minimum levels, while with the onset of monsoon, both increase, peaking in May. This coherence stems from water molecules condensing in the air, elevating both humidity and precipitation. In winter, humidity rises faster than precipitation due to low temperatures prompting water vapor condensation. This close relation between precipitation and relative humidity indicates the strong role of atmospheric moisture accessibility in regulating seasonal rainfall patterns. Interannual changes highlight that years with delayed or weaker monsoon onset show a lag in the simultaneous peak of humidity and precipitation. Understanding this relationship is vital for agricultural planning and water resource management, as it directly disturbs soil moisture, crop growth, and local hydrological cycles. Table 6 confirms a direct relationship between precipitation and relative humidity through positive correlation coefficients. The correlation and regression examine offer insight into the strength and direction of relationships among key climate variables. For instance, negative correlations between maximum temperature and precipitation show that pre-monsoon heat peaks are naturally followed by monsoon rainfall, reflecting seasonal climate dynamics. Positive correlations between precipitation and relative humidity give the direct effect of atmospheric moisture on rainfall patterns, highlighting the interconnected nature of climatic parameters that is important for agricultural planning and water resource management.

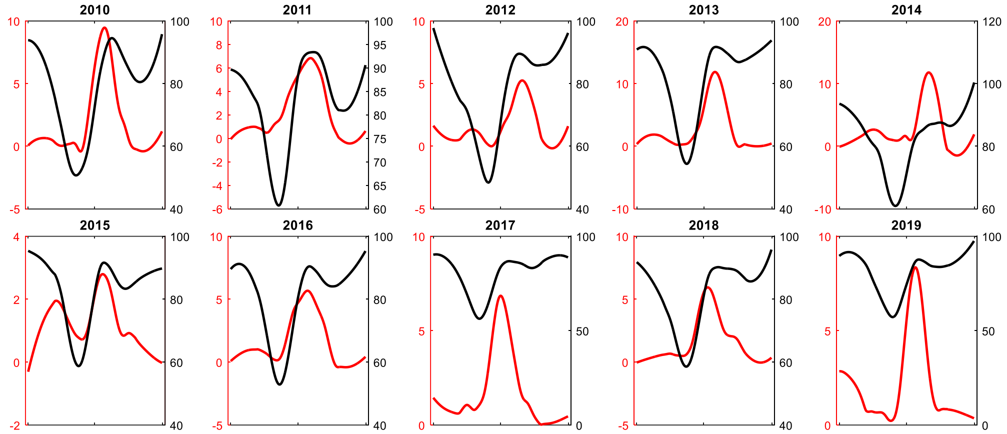

Figure 8. Relation of precipitation and relative humidity (red curve shows precipitation while black shows relative humidity)

Table 6. LRC1 (Linear regression coefficient when precipitation is independent while relative humidity is the dependent variable), LCR2 (Linear regression coefficient when precipitation is dependent while relative humidity is independent variable), CRC (correlation coefficient)

Years	LRC1	LRC2	CRC	Years	LRC1	LRC2	CRC
2010	0.2652	0.1005	0.1632	2015	0.6983	0.0151	0.1028
2011	0.4164	0.1631	0.2606	2016	0.3728	0.0718	0.1636
2012	0.5508	0.063	0.1863	2017	0.2628	0.0644	0.1301
2013	0.3672	0.1409	0.2274	2018	0.2911	0.0550	0.1265
2014	0.1503	0.1573	0.1538	2019	0.3629	0.1122	0.2017

Uncertainty Analysis and Study Limitations:

Although the results provide useful insights into climatic variability and interactions among temperature, precipitation, and relative humidity in Lahore, several sources of uncertainty should be acknowledged. First, the study combines precipitation data obtained from NASA Giovanni with temperature and relative humidity observations collected from Weather Underground station records. Differences in spatial resolution, measurement approaches, and data acquisition procedures may introduce uncertainty into comparative analyses. Second, minor missing values in the climatic records were addressed using interpolation and temporal aggregation techniques. Although missing observations represented a limited portion of the dataset and are not expected to substantially affect long-term trends, some uncertainty may remain in reconstructed values. Third, the statistical methods adopted in this study, including linear regression and correlation analysis, quantify the strength and direction of relationships among variables but do not establish causal mechanisms or fully capture non-linear climatic interactions.

Recommendations: Based on the observed trends in precipitation, temperature, and relative humidity in Lahore, several evidence-based recommendations are proposed to support climate adaptation and sustainable resource management.

The precipitation analysis revealed considerable interannual variability (CV ≈ 25%), indicating the need for adaptive water-resource management and climate-responsive planning. Agricultural stakeholders should adjust crop calendars and irrigation scheduling according to seasonal rainfall fluctuations and promote drought- and climate-resilient crop varieties to reduce production risks.

Although temperature variability remained comparatively low (CV ≈ 1.20%), the observed temporal fluctuations suggest the importance of implementing heat adaptation measures. Urban planners should expand urban green spaces, encourage heat-resilient infrastructure, and strengthen urban design strategies that reduce heat accumulation and improve thermal comfort, particularly during warmer periods.

Similarly, the relatively stable relative humidity conditions (CV ≈ 2.06%) indicate persistent atmospheric moisture conditions that may influence crop growth, evapotranspiration, and human thermal comfort. Therefore, agricultural and environmental planning should incorporate humidity-related indicators into irrigation management, crop selection, and seasonal adaptation strategies.

In addition, continuous climate monitoring and improved meteorological observation networks should be prioritized to support early warning systems and evidence-based decision-making. Integrating localized climate information into environmental and urban policies can strengthen long-term climate resilience and sustainable development planning in Lahore.

Conclusion:

Over the past decade, the climate of Lahore has undergone change, leading to reported variations in key climate parameters. This study aimed to assess environmental factors, including temperature, precipitation, and relative humidity, while investigating their interrelationships in pre-2020 period. Notably, the precipitation rate surges in July and August due to the monsoon season, with 2013 and 2017 being the wettest years, and 2015 emerging as the driest. A consistent relative humidity variation pattern spanning 2010 to 2019 reveals minimum levels in May, except for 2014. Correlations emerge: inverse between relative humidity and maximum temperature, and direct between summer precipitation and maximum temperature. Maximum temperature's pattern mirrors that of previous years, except for 2014, peaking typically in late May. Linear regression and correlation coefficients affirm the inverse relationship of maximum temperature with relative humidity and precipitation, whereas a direct relationship exists between precipitation and relative humidity, supported by positive coefficients that can guide adaptive strategies in agriculture, with crop selection and irrigation scheduling, as well as inform urban planning to mitigate heat stress and optimize water management. These results highlight the importance of integrating local climate variability data into decision-making for climate-resilient progress in Lahore, mainly in preparation for near-future projections in post 2019.

Practical Implications and Policy Relevance:

The findings of this study provide important practical insights for climate adaptation and sustainable environmental management in Lahore. The observed interannual variability in precipitation and changing temperature and relative humidity conditions indicate increasing pressure on water availability, urban infrastructure, and climate-sensitive sectors.

From an agricultural perspective, the identified climatic variability can support improved crop scheduling, irrigation planning, and seasonal decision-making. Since agricultural productivity in Pakistan strongly depends on precipitation and atmospheric conditions, understanding temporal climate behavior may contribute to reducing climate-related risks and improving resource efficiency.

For urban management, the observed climatic variations highlight the need for climate-resilient planning approaches. Variability in precipitation may increase urban drainage challenges and flood vulnerability, while temperature fluctuations can intensify heat-related stress and increase energy demand. These findings may assist planners in developing adaptive infrastructure and improving urban environmental resilience.

The results provide a clearer understanding of the interrelationships among temperature, precipitation, and relative humidity in Lahore, offering a useful climatic baseline for future hydro-climatic and variability studies in the region.

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