Trend Analysis and Prediction for Extreme Temperature of Lahore, Pakistan

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This paper aims to examine the trends of the maximum temperature (Tmax) and minimum temperature (Tmin) in Lahore over a period of 42 years (1988 to 2029). The study employs the Mann-Kendall statistical test to analyze the linear trends of both Tmin and Tmax annually and seasonally. To determine the linear trends in temperature extremes (Te), a linear curve fitting method was employed. In modeling Tmax and Tmin, a sine function was utilized. The results showed that Tmin exhibited an increasing trend both annually and seasonally, except for winter, where no significant trend was observed. Conversely, Tmax showed a decreasing trend both annually and seasonally, except for the monsoon and pre-monsoon periods, where no significant trends were found. Furthermore, the study divided the Te data from 1988 to 2019 into two time series: from 1988 to 2003 and from 2004 to 2019. The findings indicated that Tmin had no significant trend, while Tmax demonstrated an increasing trend for the first time series. In contrast, both Tmin and Tmax exhibited increasing trends for the second time series. Moreover, when the time series was divided into six parts for trend analysis, mixed trends, whether increasing or decreasing, were observed. To investigate the periodicity of Te, the sine function was applied, and the results showed that Tmin had no periodicity. However, Tmax exhibited periodicity, and it was observed that the peak pattern repeated in reverse after 2004. Based on the proposed sine function model, the study predicted the future pattern of the maximum temperature variation in Lahore for the next ten years (i.e., 2020 to 2029).

Keywords: Linear and Non-Linear Trends; Upper and Lower Peaks; Temperature Prediction

Introduction:

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013) reported a temperature increase of approximately 0.72°C, with a range between 0.49°C and 0.89°C, based on a linear trend [1]. The report reaffirmed the findings of the Fourth Assessment Report (AR4), indicating that, on a global scale, the frequency of cold nights and days has decreased, whereas the occurrence of warm nights and days has increased. Global warming is currently one of the most significant challenges facing the planet [2]. The ongoing rise in greenhouse gas emissions is significantly impacting the Earth's climate [3][4]. Anthropogenic activities during the Industrial Revolution in the 1700s-1800s caused significant changes to the Earth's climate [5]. Climate change and its variability have a significant impact on agricultural countries such as Pakistan, with temperature defining the growing season of an area [6].

The global average surface temperature has risen over the past century and is projected to increase further throughout the 21st century, posing a significant threat to socioeconomic systems across the globe. This increase in temperature has also led to a decrease in snowfall [7]. Atmospheric warming is responsible for significant variations in temperature, precipitation, humidity, and sea surface temperatures [8], which collectively drive the broader phenomenon of climate change [9][3][10]. This shift in mean temperature also results in extreme events like heatwaves and cold spells occurring in certain regions [11].

[12] reported no significant increasing trend in the annual mean temperature of the upper Indus River, while an increasing trend is observed in the north Himalayan region since the 19th century [13]. This upward temperature trend is regarded as one of the primary drivers of glacier melting [14]. Furthermore, the analysis of spatiotemporal variations in land surface temperature in Jubail Industrial City has proven valuable for climate change modeling efforts [15]. In addition, the Mann-Kendall and Sen's slope estimator have been used to analyze the trend of temperature and rainfall in the Tano River basin of Ghana. Using historical data from 1986 to 2015, projections have been made for the period 2021–2050, providing valuable insights for effective water resource management [16]

AR5 reports that the annual mean temperature has increased in most regions of Asia over the past century (IPCC 2013). Notably, between November and March (cold season), a stronger warming trend was observed from 1901 to 2009, with a 2.4C °C increase in mid-latitude semiarid areas of Asia. In the present context, the year 2009 is still recognized as one of the top five warmest years on record since 1850, as reported by the World Meteorological Organization [17].

Pakistan ranks third among the countries most affected by climate change, according to the think tank "Germanwatch" [18]. Between 1947 and 2000, the country's surface temperature increased by 5% over a span of 50 years, based on linear trend analysis. This rise reflects the growing impact of population expansion, greenhouse gas emissions, and rapid industrialization particularly in recent decades [19]. This temperature rise has adversely affected the growth cycle of the maize crop in Faisalabad [20].

While changes in mean temperature are often used as an indicator of climate change, analyzing changes in both maximum and minimum temperature can provide more comprehensive information [21]. The IPCC's fifth assessment report notes that trends in mean temperature are a result of changes in either maximum or minimum temperature, or both, with relative changes in both variables (IPCC 2013). However, the trends in maximum and minimum temperature are not uniform across space and time [22]. Numerous studies have investigated temperature trends in various Asian countries, including India [14], Turkey [23], and Malaysia [7].

Several studies have investigated temperature extremes in Pakistan at various temporal and regional scales. In particular, studies have focused on major cities within the country. [24]

examined extreme temperature variations in the five major cities from 1961 to 2007. Another study by [19] investigated trends in maximum, minimum, and mean temperatures in Karachi from 1947 to 2005. In the study, findings indicate that the maximum temperature has a more pronounced influence on the overall rise in temperature in Karachi than the minimum temperature. [25] conducted a study on the mean temperature trend of Faisalabad from 1945 to 2004, while [26] analyzed the diurnal temperature range from 1979 to 2008 over Chaklala in Islamabad. [13] investigated the impact of climate change on water and agriculture in the mountain region of Pakistan during winter and monsoon. In the present context, studies by [27] and [28] on trends in maximum and minimum temperatures in the Upper Indus River Basin continue to offer valuable insights into regional climate patterns across various parts of Pakistan. [29] analyzed temperature trends in the Karakoram region and their potential impacts on glaciers. [30] conducted spatiotemporal analyses of different pollutants, such as sulfur dioxide, ozone, and nitrogen oxides, in and around the Great Smoky Mountains National Park in the United States from 1989 to 2016, using piecewise regression lines. [31] investigated long-term meteorological climate trends in the middle and lower Indus basins of Pakistan. [32] tested weather trends in maximum and minimum temperature, as well as diurnal temperature range, both annually and seasonally in the Mangla watershed. [33] conducted a comprehensive study on the climate profile and past changes in the climate of Pakistan, including trend analysis for maximum and minimum temperature.

Although several studies on temperature leanings across Pakistan [34], Lahore, Pakistan's second-largest city, is rarely the direct focus of detailed long-term temperature analyses, while regional assessments capture broader climate dynamics and overlook how urbanization-driven changes in land cover and landscape structure directly influence local temperature extremes in Lahore [35]. Similarly, there is limited assessment of seasonal and inter-period trends, or predictive modeling of Tmax and Tmin designed for the city's thermal environment. Previous studies have relied heavily on remote sensing and landscape metrics to link land surface temperature (LST) with built environment changes, but fewer have employed statistical trend analyses like the Mann-Kendall test or sine-based periodic modeling to forecast temperature extremes within Lahore's urban context [36]. This study fills the gap by using city-specific temperature data, applying robust statistical trend testing and sine-function modeling, and providing future temperature predictions for Lahore.

Novelty Statement:

Numerous studies have been conducted on temperature analysis in Pakistan; however, there is a lack of research on temperature analysis specifically in the megacity of Lahore. The novelty of this study lies in incorporating the Mann-Kendall test with a sine function model to gather both linear trends and periodicity in Lahore's temperature extremes. Additionally, it uniquely identifies after-2004 variations in Tmax's periodic peak pattern and projects its future variation up to 2029. We aim to examine the trends of both Tmin and Tmax over the past 32 years (1988 to 2019), as well as predict the future variations in maximum temperature for the next decade. This study intends to fill the gap in knowledge about temperature analysis in Lahore and provide valuable insights into the city's changing climate patterns.

Material and Methods:

Study Area and Data: Lahore is one of the major cities of Pakistan. Lahore is the capital of the province of Punjab. It is located between 31o15'-31o45'N and 70o01'-74o45'E. It is situated on the northern side of the Ravi River, covering approximately 1019 square kilometers of land, and is heavily populated. The city experiences four distinct seasons: winter (January-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-December) [37]. June is known to be the hottest month with an average high temperature exceeding 40 degrees Celsius (104 degrees Fahrenheit). July is the wettest month, with frequent heavy rainfall and evening thunderstorms. On the other hand, January is typically the coldest month with the occurrence of intense fog.

Figure 1. Map of Lahore

Therefore, Lahore is classified as having a hot semi-arid climate, with mean annual precipitation around 600–760 mm and an average annual temperature of approximately 24 °C [38]. Rapid urban growth has changed Lahore's microclimate significantly. Between 1998 and 2021, built-up area nearly doubled from ~10 % to ~39 % of total land while vegetation and water bodies declined proportionally [36]. The flow diagram of this study is given in Figure 2. For the completion of the first step, we obtained data from the Meteoblue Switzerland website (https://www.meteoblue.com/), which provides weather information for locations around the world, both on land and at sea. The website was initially developed by the University of Basel, Switzerland, based on data from NOAA/NCEP.

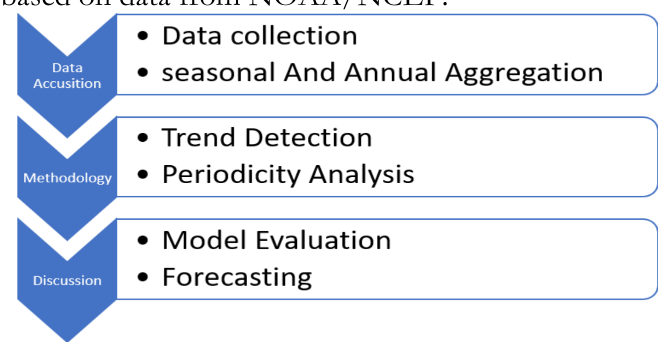

Figure 2. Flow diagram of the Study

Data Processing and Trend Analysis Method:

To investigate the linear trends in maximum and minimum temperatures, the present study employed the Mann-Kendall (MK) test, a non-parametric method widely used for detecting monotonic trends in climatological time series data. The rates of temperature increase or decrease were calculated using a linear curve fitting method, specifically a polynomial of degree 1. The linear model was selected for its simplicity, interpretability, and robustness, specifically over a moderate-duration dataset, reducing the risk of Overfitting.

For non-linear trend analysis and future temperature pattern predictions, we employed the sine function. The sinusoidal model is normally applied to average monthly or seasonal temperatures because it aligns with physical occurrences (Earth's orbit/solar cycle) and carries strong goodness-of-fit with nominal complexity [39].

To evaluate the annual trends of maximum and minimum temperatures, we calculated the mean of daily data for each respective year. Statistical trends can be detected over time using both parametric and non-parametric procedures. In this study, we utilized the MK test to conduct a statistical analysis of significant trends.

Mann–Kendall Test:

The Mann-Kendall (MK) test is a statistical method used to evaluate the null hypothesis of no trend versus the alternative hypothesis of a monotonic decreasing or increasing trend in hydro-climatic time series data. For data sets with at least 10 data points, the Z-statistic can be used to determine the trend in the time series data. A positive Z value indicates an upward (increasing) trend, while a negative Z value indicates a downward (decreasing) trend. The Z-value is calculated using the following equation, originally proposed by Mann in 1945 and later refined by Kendall in 1955 [40-41]. This statistical approach forms the basis of the Mann-Kendall test, which is widely used for detecting trends in climatological and hydrological time series data.

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

var(S) and S are

$$Var(S) = \frac{1}{18}\left\{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p-5)\right\} \quad (2)$$

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} f(x_j - x_i) \quad (3)$$

Where, x_i and x_j are annual values of the year i and j, j>i respectively, n is number of data points and $f(x_j - x_i)$ is calculated by:

$$f(x_j - x_i) = \begin{cases} 1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases} \quad (4)$$

To investigate the performance of statistical models, the selected parameters are

Coefficient of Determination (R^2):

The coefficient of determination, denoted by R^2, measures how well the regression model explains the observed variability of the dependent variable, such as temperature. Mathematically, R^2 is:

$$R^2=1-x/y \quad (5)$$

where x is the residual sum of squares and y is the total sum of squares, total variance in the data [42].

Sum of Squared Error (SSE):

The Sum of Squared Errors (SSE) is used to calculate the precision of a model's predictions. It is generally employed in the context of regression analysis and machine learning. Mathematically, SSE can be described as:

$$SSE = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \quad (6)$$

Where n is the data point, yi is the observed value for the ith data point, and yi^is the predicted (or modeled) value for the ith data point.

Root Mean Square Error (RMSE):

MSE is calculated as the square root of the mean of the squared residuals (differences between observed and predicted values) [43]

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (7)$$

Result and Discussion:

This paper presents a comprehensive trend analysis of temperature in Lahore covering the period from 1988 to 2019, along with predictions of temperature patterns for the subsequent 10 years following 2019.

Trends of Minimum Temperature:

Linear Trend:

The analysis of temperature trends from 1988 to 2019 revealed an increasing trend in Tmin, as depicted in Figure 3. In the past, the minimum temperature (Tmin) increased at a rate of 0.04782°C per decade (Fig. 3). A sharp rise in Tmin was particularly evident between 2012 and 2013. However, when the time series was divided into two parts, namely 1988 to 2003 and 2004 to 2019, the first part shows no remarkable trend in Tmin, as the slope is approximately zero (Figure. 4a). In contrast, Tmin exhibits an upward (increasing) trend during the second part of the time series, with an increased rate of 0.06877°C/decade (Figure 4a).

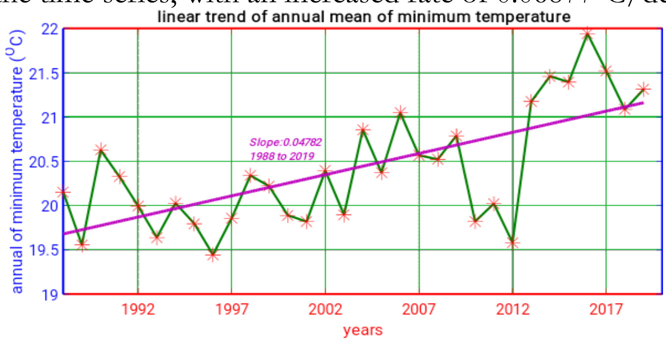

Figure 3. Trend of minimum temperature (CO) for the period from 1988 to 2019

Based on the analysis of six different time series, the trend of Tmin (minimum temperature) varies throughout the years. The period from 1988 to 1992 and 2003 to 2007 showed an upward trend, with an increase rate of 0.04554°C/decade and 0.1533°C/decade, respectively. Notably, the increase rate of Tmin from 2003 to 2007 is higher than that from 1998 to 1992. In contrast, Tmin decreased during the periods of 1993 to 1997, 1998 to 2002, 2008 to 2012, and 2013 to 2019, with a decreasing rate of -0.0149°C/decade, -0.02933°C/decade, -0.2644°C/decade, and -0.00767°C/decade, respectively. It is worth noting that the decline in Tmin between 2008 and 2012 occurred at a faster rate compared to other time intervals, as illustrated in Fig. 4b.

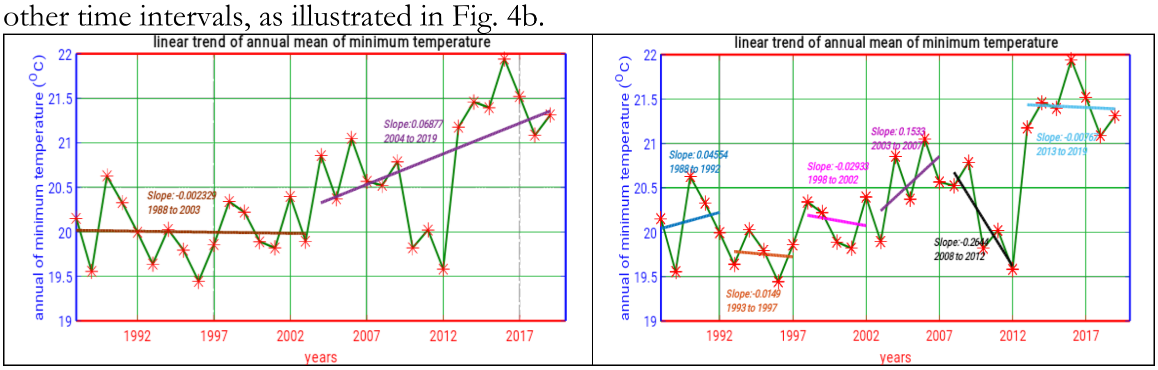

Figure 4. Trends of Tmin (in OC) (a) when Tmin is divided into 2 time series (b) when Tmin is divided into 6 time series

Table 1. Goodness of fit, null hypothesis (at the alpha significance level 0.1), trend, and slope of annual mean minimum temperature.

	1988 to 1992	1993 to 1997	1998 to 2002	2003 to 2007	2008 to 2012	2013 to 2019
Goodness of fit	SSE: 0.6108	SSE: 0.193	SSE: 0.2672	SSE: 0.5639	SSE: 0.2931	SSE: 0.465
	R-square: 0.03284	R-square: 0.01137	R-square: 0.0312	R-square: 0.2941	R-square: 0.7046	R-square: 0.00353

	Adjusted R-square: -0.2895	Adjusted R-square: -0.3182	Adjusted R-square: -0.2917	Adjusted R-square: 0.0588	Adjusted R-square: 0.6062	Adjusted R-square: -0.1958
	RMSE: 0.4512	RMSE: 0.2537	RMSE: 0.2984	RMSE: 0.4336	RMSE: 0.3126	RMSE: 0.3049
Slope	0.04554	-0.0149	-0.02933	0.1533	-0.2644	-0.00767
Trend	Increasing	Decreasing	Decreasing	Increasing	Decreasing	No remarkable decreasing trend
	1988 to 2003			2004 to 2019		
goodness of fit	SSE: 1.591			SSE: 4.884		
	R-square: 0.001158			R-square: 0.2477		
	Adjusted R-square: -0.07019			Adjusted R-square: 0.1939		
	RMSE: 0.3372			RMSE: 0.5906		
Slope	-0.002329			0.06877		
P-value	0.9641>0.1			0.0649<0.1		
Null Hypothesis	Accepted			Rejected		
Z	0			1.8459 (Positive)		
Trend	No trend			Increasing		
	1988 to 2019					
goodness of fit	SSE: 7.527					
	R-square: 0.4532					
	Adjusted R-square: 0.435					
	RMSE: 0.5009					
Slope	0.04782					
P-value	0.00023<0.1					
Null Hypothesis	Rejected					
Z	3.6811 (Positive)					
Trend	Increasing					

Seasonal Trends:

The city of Lahore experiences four seasons, namely, winter (January to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to December). Analysis shows that there is an upward trend in Tmin (minimum temperature) during the pre-monsoon, monsoon, and post-monsoon seasons. Between 1988 and 2019, the minimum temperature (Tmin) increased at seasonal rates of 0.05453°C/decade, 0.06658°C/decade, and 0.04848°C/decade, respectively, indicating a consistent warming trend across different times of the year. In contrast, there was no discernible trend in Tmin during the winter season, with a rate close to zero (-0.002874°C/decades). Therefore, it can be concluded that Tmin during winter remained relatively consistent from 1988 to 2019. Overall, the analysis shows that the maximum rate of increase in Tmin occurred during the monsoon season, with a rate of 0.06658°C/decades (as shown in Figure 5).

Table 2. Seasonal trends, the goodness of fit, and the slope of the minimum temperature Tmin

	Winter	Pre-monsoon	Monsoon	Post-monsoon
goodness of fit	SSE: 36.19	SSE: 14.02	SSE: 19.46	SSE: 18.28

	R-square: 0.0006221	R-square: 0.3666	R-square: 0.3833	R-square: 0.2596Adjusted R-square: 0.235
	Adjusted R-square: -0.03269	Adjusted R-square: 0.3454	Adjusted R-square: 0.3627	RMSE: 0.7806
	RMSE: 1.098	RMSE: 0.6836	RMSE: 0.8054	SSE: 18.28
Slope	-0.002874	0.05453	0.06658	0.04848
P-value	0.6615>0.1	2.3220e^{-04}<0.1	0.0027<0.1	0.0263<0.1
Null Hypothesis	Accepted	Rejected	Rejected	Rejected
Z	0	3.6811 (Positive)	3 (Positive)	2.2217(Positive)
Trend	No trend	Increasing	Increasing	Increasing

Figure 5. Seasonal trends Tmin (in OC) (a) winter (January to February) (b) pre-monsoon (March to May) (c) monsoon (June to September) (d) post-monsoon (October to December)

Non-Linear Trend:

While a sine function of mode 6 offered the best fit for Tmin during sinusoidal trend analysis through curve fitting, the results indicate that Tmin does not follow a clearly defined pattern, as illustrated in Figure 6.

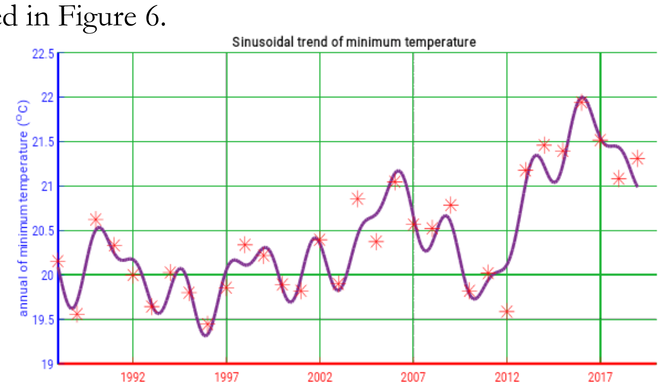

Figure 6. The trend of Tmin by using sinusoidal curve fitting for the period (1988

Trends of Maximum Temperature:

Linear Trends:

The trend of the annual mean of Tmax was assessed using the MK statistical method, and the magnitude of the slope was calculated by curve fitting with a linear polynomial of degree 1. The analysis revealed a downward (decreasing) trend of Tmax with a decrease rate of -0.01905°C/decade, as shown in Figure 6. While there was an increase in Tmax during the period from 1998 to 2003, it was followed by a sudden decrease in 2003, and subsequent increases from 2005 to 2008. However, even with these increases, Tmax remained lower than the temperatures observed during the 1998–2003 period, which explains the negative slope indicating a decreasing trend in Tmax over the past 32 years. Tmax remained lower than the temperatures recorded during the 1998-2003 period. This is the reason behind the negative slope (decreasing trend) of Tmax over the last 32 years.

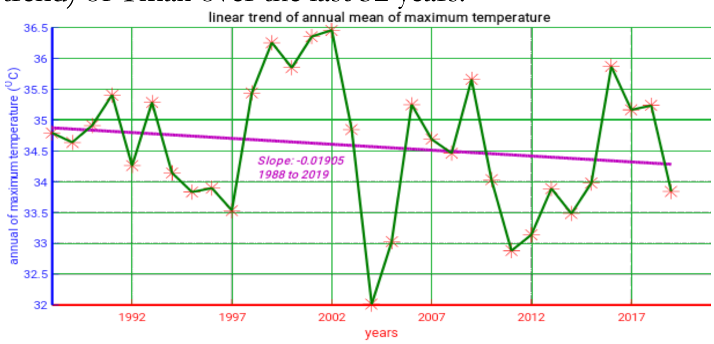

Figure 7. Annual trend of maximum temperature (in OC) for the period from 1988 to 2019

To further investigate the trend of Tmax, we divided the data into two time series, each containing 16 data points: (1) from 1988 to 2003 and (2) from 2004 to 2019. The analysis showed an upward (increasing) trend in Tmax for both time series, with a rate of increase of 0.08426°C/decade for the period from 1988 to 2003 and 0.07564°C/decade for the period from 2004 to 2019. Interestingly, both time series exhibited similar rates of increase. Furthermore, it was observed that the annual mean of Tmax reached its minimum in 2004 and peaked in 2002, as illustrated in Figure 8.

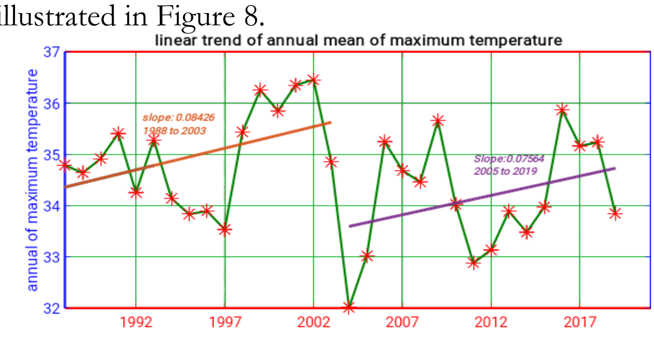

Figure 8. Trend of Tmax (OC), time series is divided into two parts: from 1989 to 2003 and from 2004 to 2019.

To further analyze the trend of Tmax, we divided the temperature time series into six parts, covering the periods of (1) 1988 to 1992, (2) 1993 to 1997, (3) 1998 to 2002, (4) 2003 to 2007, (5) 2008 to 2012, and (6) 2013 to 2019. An upward (increasing) trend was observed for time series 3, 4, and 6, with rates of increase of 0.2131°C/decade, 0.2919°C/decade, and 0.1627°C/decade, respectively. The increase rate of Tmax was the highest for time series 4 (2003 to 2007) due to its maximum slope, while time series 6 (2013 to 2019) had the lowest increase rate because it had the minimum positive slope among all. On the other hand, time series 1, 2, and 5 exhibited a downward (decreasing) trend, with respective decline rates of -0.2982°C/decade, -0.375°C/decade, and -0.5418°C/decade, as depicted in Figure 9. Tmax decreased with the maximum rate from 2008 to 2012 due to its maximum slope.

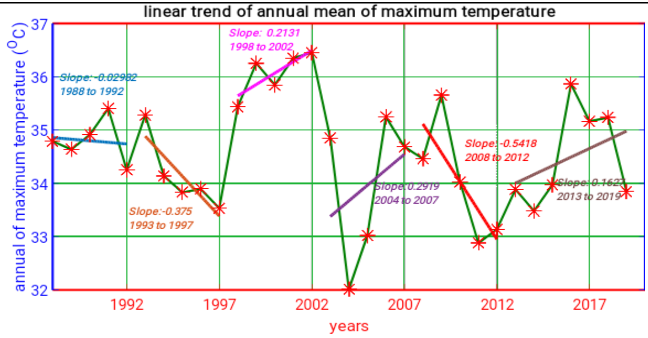

Figure 9. Trend of Tmax (OC) when the time series is divided into six parts: time series.

Table 3. Goodness of fit, null hypothesis (at the alpha significance level 0.1), slope, and trend of the annual mean of maximum temperature

	1988 to 1992	1993 to 1997	1998 to 2002	2003 to 2007	2008 to 2012	2013 to 2019
goodness of fit	SSE: 0.6902	SSE: 0.4277	SSE: 0.2553	SSE: 6.792	SSE: 2.008	SSE: 4.212
	R-square: 0.01272	R-square: 0.7668	R-square: 0.6402	R-square: 0.1114	R-square: 0.5939	R-square: 0.1496
	Adjusted R-square: -0.3164	Adjusted R-square: 0.689	Adjusted R-square: 0.5203	Adjusted R-square: -0.1848	Adjusted R-square: 0.4585	Adjusted R-square: -0.02049
	RMSE: 0.4797	RMSE: 0.3776	RMSE: 0.2917	RMSE: 1.505	RMSE: 0.818	RMSE: 0.9178
Slope	-0.02982	-0.375	0.2131	0.2919	-0.5418	0.1627
Trend	Decreasing	Decreasing	Increasing	Increasing	Decreasing	increasing
	1988 to 2003			2004 to 2019		
goodness of fit	SSE: 10.49			SSE: 16.17		
	R-square: 0.1871			R-square: 0.1073		
	Adjusted R-square: 0.129			Adjusted R-square: 0.04359		
	RMSE: 0.8656			RMSE: 1.075		
Slope	0.08426			0.07564		
P-value	0.1628<0.5			0.3923<0.5		
Null Hypothesis	Rejected			Rejected		
Z	1.3957 (Positive)			1 (Positive)		
Trend	Increasing			Increasing		
goodness of fit	SSE: 35.55					
	R-square: 0.02708					
	Adjusted R-square: -0.005349					
	RMSE: 1.089					
Slope	-0.01905					
P-value	0.3553<0.5					
Null hypothesis	Rejected					
Z	-1 (negative)					
Trend	Decreasing					
Slope	-0.01905					

Seasonal Trend:

Lahore's seasons have been classified into four categories: winter (January to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to December). We analyzed the Tmax trend from 1988 to 2019 and found a downward (decreasing) trend during winter and post-monsoon seasons, with rates of -0.0408OC °C/decade and -0.0213°C/decade, respectively. However, no significant decrease in Tmax was observed during the pre-monsoon and monsoon seasons, as their trend slopes were nearly zero, indicating a relatively stable temperature pattern during these periods (Figure 10).

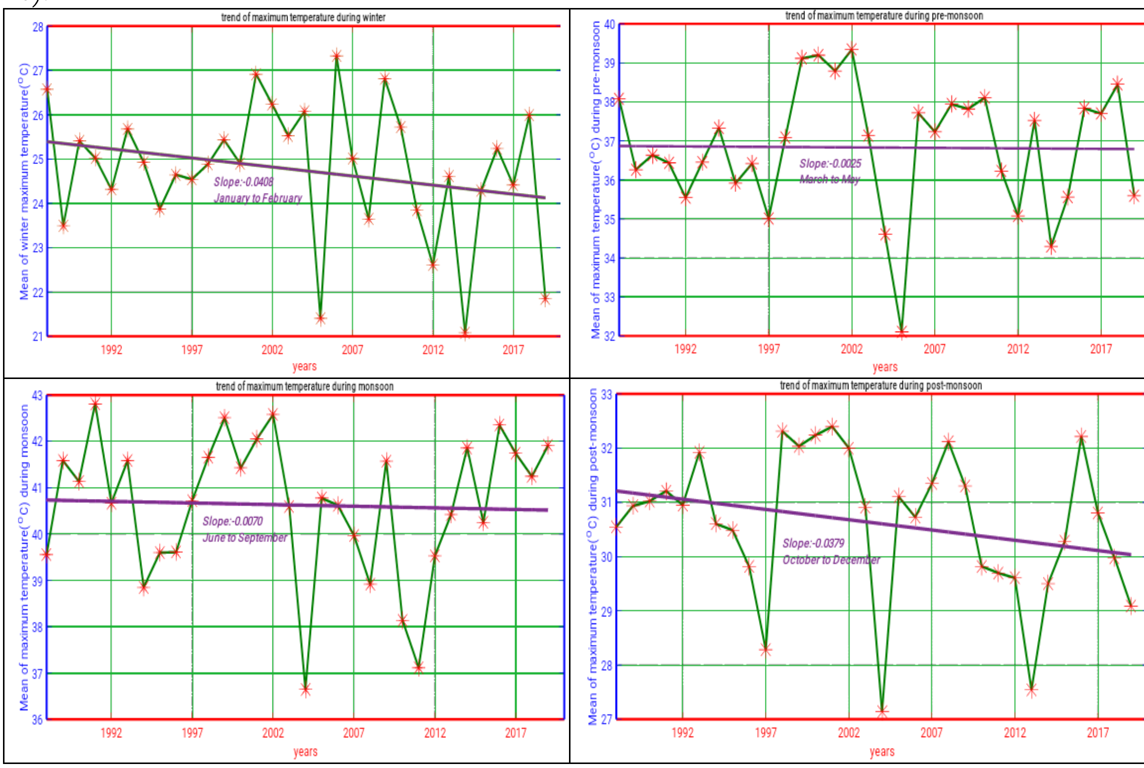

Figure 10. Seasonal trends of Tmax (OC) for (a) winter (January-February), (b) pre-monsoon (March-May), (c) monsoon (June-September), (d) post-monsoon (October-December)

Table 4. Seasonal trend, the goodness of slope, the null hypothesis (at the alpha significance level 0.1), and the slope of maximum temperature

	Winter	Pre-monsoon	Monsoon	Post-monsoon
goodness of fit	SSE: 66.27	SSE: 79.36	SSE: 71.98	SSE: 51.57
	R-square: 0.06427	R-square: 0.0002137	R-square: 0.001865	R-square: 0.0705
	Adjusted R-square: 0.03308	Adjusted R-square: -0.03311	Adjusted R-square: -0.03141	Adjusted R-square: 0.03951
	RMSE: 1.486	RMSE: 1.626	RMSE: 1.549	RMSE: 1.311
Slope	-0.04085	-0.002493	-0.007021	-0.03787
P-value	0.3724<0.5	0.8078>0.5	0.9871>0.5	0.1234<0.5
Null hypothesis	Rejected	Accepted	Accepted	Rejected
Z	-1 (negative)	0	0	-1.5406 (negative)
Trend	Decreasing	No trend	No trend	Decreasing

Non-Linear Trend:

From Figure 11, it is evident that the variation of Tmax is periodic. Tmax is divided into six regions (1 to 6) based on the temperature variation around the mean value of each region, as shown in Figure 11. Each region displays three extreme temperature values. For Region 1, spanning from 1989 to 1993, the mean temperature was approximately 34.5°C, with the highest recorded temperature reaching 35.4°C in the year 1991. After 1994, the temperature decreases, and region 2 begins, where the temperature has two minimum values in 1994 and 1997, with a mean value of approximately 34.1°C. Region 3 (post-1998) exhibits the highest mean temperature, approximately 36°C, compared to the other regions. Within this period, Tmax followed a fluctuating trend rising from 1998 to 1999 and then gradually declining through 2000 at a slower rate. After region 3 (2003), the temperature decreases until 2004, after which it starts increasing again. The next regions (4, 5, and 6) are roughly similar to regions 3, 5, and 6, respectively. Therefore, it can be inferred that the temperature variation after 2004 appears to be a mirror reflection of the pattern observed before 2004, indicating that the year 2004 serves as a focal point or turning point in the temperature trend.

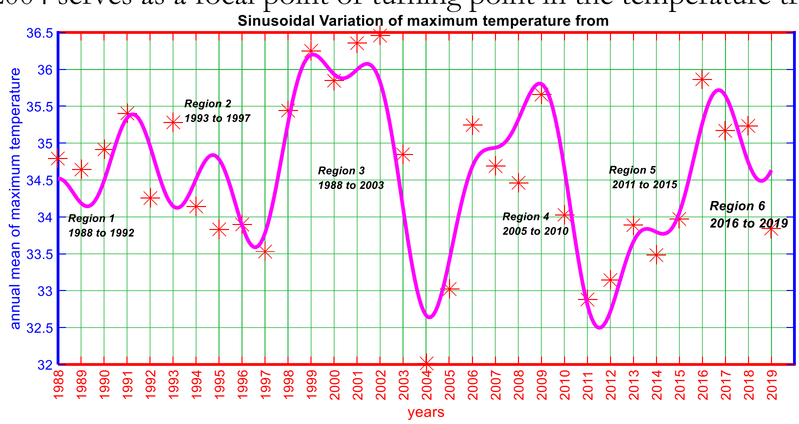

Figure 11. The sinusoidal Variation of Tmax (OC) for the period from 1988 to 2019

Peak Analysis:

The peak analysis has been done in two parts.

Upper peaks

Lower peaks

Upper peaks (above 34.5 °C):

Based on the analysis, upper peaks in Tmax exceeding 34.5°C were identified in the years 1988, 1991, 1995, 1999, 2001, 2006, 2009, 2013, 2016, and 2019. Interestingly, the peaks from 1988 to 2001 exhibit a pattern that closely mirrors those from 2006 to 2019, suggesting a cyclical trend in maximum temperature variation over the decades. It has also been observed that the temperature peaks occurring before 2004 reappear after 2004 in reverse order, following a distinct sequential pattern. This further supports the idea of 2004 acting as a central turning point in the Tmax trend. The formula $5(6-n_0)$, where n_0 is 0, 1, 2, 3, and 4, can be used to predict the occurrence of these peaks, except for the peak found in 1995, which reappeared after 18 years in 2013.

Lower peaks (below 34.5 °C):

The lower peaks, which lie below 34.5°C, were observed in 1990, 1994, 1995, 1997, 2000, 2007, 2011, 2014, and 2018. It is noticed that peaks at 1990, 1994, 1997, and 2000 correspond to the peaks found in 2018, 2014, 2011, and 2007, respectively. Peaks before 2004 have been observed after 2004 in reverse order and follow a sequence. According to formula $7(4-n_0)$, where n_0 takes values 0, 1, 2, and 3, the observed peaks generally follow a predictable sequence. However, an exception is the peak recorded in 1994, which does not conform to this pattern and instead reappears after a 20-year interval in 2014.

Table 5. Peak analysis

Peaks at years before 2004	Magnitude of temperature at peaks (^{O}C)	years between	Similar peaks appears at years after 2004	Magnitude of temperature at peaks (^{O}C)
	Upper peaks Above 34.5^{O}C			
1988	34.79	31	2019	34.69
1991	35.4	25	2016	35.86
1995	33.83	18	2013	33.9
1999	36.25	10	2009	35.65
2001	36.35	5	2006	35.25
	Lower peaks Below 34.5 ^{O}C			
1990	34.91	28	2018	35.23
1994	34.14	20	2014	33.48
1997	33.53	14	2011	32.89
2000	35.85	7	2007	34.69

Prediction of Maximum Temperature:

The proposed model is constructed with the help of the fitting method (sine function of mode 4). This function is the sum of four sine function terms as given below:

$$F(\mathrm{x}) = \mathrm{a}_1 \sin \sin (\mathrm{b}_1\mathrm{x} + \mathrm{c}_1) + \mathrm{a}_2 \sin \sin (\mathrm{b}_2\mathrm{x} + \mathrm{c}_2) + \mathrm{a}_3 \sin \sin (\mathrm{b}_3\mathrm{x} + \mathrm{c}_3)\ \mathrm{a}_4 \sin \sin (\mathrm{b}_4\mathrm{x} + \mathrm{c}_4) \quad (8)$$

Where a, b, and c are constant. The values of the constants used in the function are dependent on the length of the dataset. Utilizing this function, the variation in Tmax from 2014 to 2019 was first predicted and validated, as illustrated in Figure 12. In the second phase, the function was applied to forecast future Tmax trends.

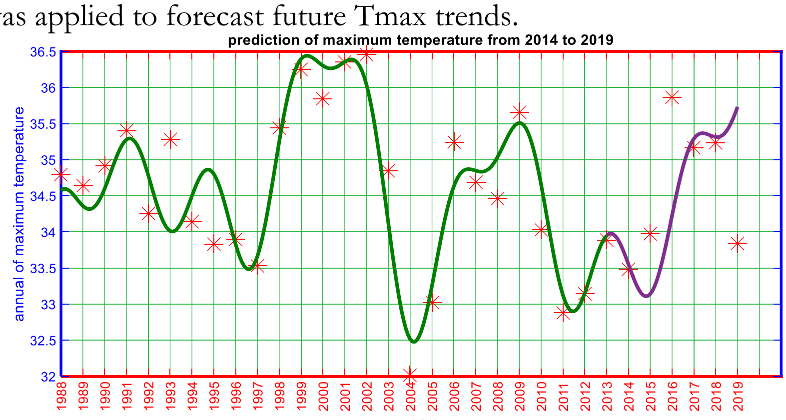

Figure 12. Prediction of Tmax from 2014 to 2019: the green curve shows fitted data of Tmax (red stars) from 1988 to 2013, and the purple curve represents the prediction for the period from 2014 to 2019

Using the proposed model, predictions for Tmax over the next 10 years (2020 to 2029) were made by applying a sine function of mode 4. The projected temperature pattern is illustrated in Figure 13. Since temperatures from 2004 to 2019 are mirror reflections of temperatures from 1988 to 2003, we can assume that temperatures from 2022 to 2029 will be mirror reflections of temperatures from 2004 to 2021. This means that the year 2022 will play the same role as the year 2004 did in the previous mirror reflection.

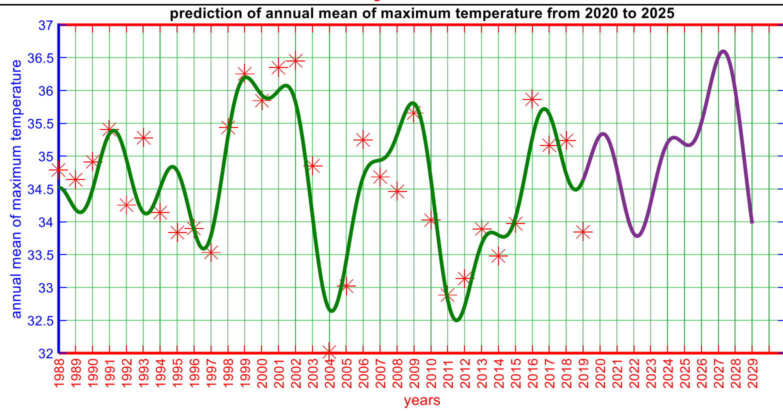

Figure 13. Prediction from 2020 to 2029: the green curve is showing fitted data of Tmax (red stars) from 1988 to 2019, and the purple curve represents the prediction for the period from 2020 to 2029

Conclusion:

This paper examines the trends in temperature (Te) in Lahore, both annually and seasonally, using data provided by meteoblue from 1988 to 2019. Linear trends in Te were analyzed using Mann-Kendall and linear curve fitting (polynomial of degree 1), while non-linear trends were investigated using curve fitting based on the sine function. From 1988 to 2019, Tmin increased at a rate of 0.04782°C/decade, while Tmax decreased at a rate of -0.01905°C/decade. However, when dividing Tmin and Tmax into two parts, no significant trend was observed for Tmin from 1988 to 2003, but from 2004 to 2019, Tmin increased at a rate of 0.06877°C/decade. On the other hand, Tmax increased at rates of 0.08426°C/decade and 0.07564°C/decade from 1988 to 2003 and 2004 to 2019, respectively. When dividing the time series into six parts, both increasing and decreasing trends were observed for Tmin and Tmax. The sine function tested up to mode 6 did not show any periodicity for Tmin, while the periodicity of Tmax was determined by the curve fitting method based on the sine function of mode 4. It was observed that Tmax from 2005 to 2019 is a mirror reflection of Tmax from 1998 to 2003. This periodicity allowed for the construction of a model to predict the future pattern of maximum temperature variation for Lahore from 2020 to 2029.

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Conflict of Interest: The Authors have no conflict of interest in publishing this manuscript in IJIST.

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