Temperature Variability Over Urban, Town, and Rural Areas: The Case of Pakistan

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TEMPERATURE VARIABILITY OVER URBAN, TOWN, AND RURAL AREAS: THE CASE OF PAKISTAN

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Abstract

This study investigates the evolution of temperatures at several locations in Pakistan. Data on annual and seasonal minimum (T_n) and maximum (T_x) temperatures from 1950 to 2013 of urban (16 stations), town (11 stations) and rural (9 stations) areas are analyzed to establish the mean decadal rate of change in urban, town, and rural temperatures. The homogeneity of the data were assessed using HOMER 2.6. To measure the temporal intensity of change in temperature, the data were split into two different periods: 1950–1981 (P1, phase of less urbanization) and 1982–2013 (P2, phase of highly urbanized period) and were analyzed separately for both phases of 32 years each. The per decade changes of annual minimum and maximum temperatures (dT_n^a and dT_x^a, respectively) over most stations show an increase of temperatures. The trends of annual and seasonal dT_n and dT_x observed over urban, town, and rural stations during P2 are significantly higher than those observed during P1. The increase in minimum temperatures is more significant than that in maximum temperature and it is also more significant on urban stations than the town and rural stations. However, the maximum temperatures increase more at town stations than urban and rural stations. Overall, the tendencies in temperatures reflect less change in summer temperatures than other seasons of the year over the whole period.

Keywords: Urbanization, urban temperature, climate change, Pakistan.

1. Introduction

Human influence on the climate through the anthropogenic emissions of greenhouse gases (GHGs) is clear. These emissions are the highest in history while the impacts of climate change (CC) on human and natural systems are known to be important. The scientific community regularly alerts the population about these impacts and the need to reduce GHGs (IPCC, 2014). During the past 50 years (1966–2015), global annual-mean surface air temperature has increased at a per decade rate of 0.21°C^{-dec} (Hansen et al., 2010). Populations must increasingly face heat waves due to this CC and urban populations are more exposed due to specific local air temperature conditions.

Within urban areas, surface air temperatures, especially at night, are several degrees higher than the simultaneous temperatures of the surrounding rural areas (Hung et al., 2006). This temperature difference between urban and surrounding non-urban areas is known as an urban heat island (UHI). This is due to a combination of several factors (Martilli et al., 2020): (1) highest absorption of the solar radiation by high buildings, enhanced by multiple reflections into

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street canyons. (2) Capture of infrared radiation emitted by warmed artificial materials into these street canyons. (3) Emissions of heat through heating or air conditioning systems, combustion in vehicles (Li et al., 2015) and industries (Portela et al., 2020). (4) Lower wind speeds that reduce heat dispersion. (5) Lack of evaporative cooling from vegetal areas (Kohler et al., 2016). The UHI concept is often used to describe "excess" heat associated with urban areas, and is therefore considered a risk for urban populations in summer that requires mitigation. Martilli et al. (2020) suggest that there are also positive effects of UHI within cities located in cold climates, as additional urban warmth reduces demand for residential heating. Cities in perennial hot climates would expect increased demand for air conditioning (AC), which transfers the indoor heat burden to the external local environment (Roth and Chow, 2012).

According to World Urbanization Prospects of the United Nations, 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050 (United Nations, 2018a). Urbanization directly affects the development of UHI. When UHI is fully developed in urbanized areas, one major question arises: is it possible to mitigate the effect of UHI to contribute to reduce heat stress? This is the focus of several studies (Viguie et al., 2020; Kim et al., 2018; Wang et al., 2016; Salamanca et al., 2012). Lemonsu et al. (2013) proposed that in the present Parisian urban climate, UHIs vary between 0 and 6°C for T_n and between −2 and 4°C for T_x. Questions are raised for developing countries: could urbanization be controlled to avoid or minimize the development of UHI? Another upcoming question is what are the urbanization effects compared to global CC on increasing the local temperatures?

Fujibe (2009) concluded that the presence of warming trend over 0.3 °C/decade in Japan, even at non-urban stations, is largely attributable to background temperature increases on a large scale, rather than the development of UHI. However, the presence of significant urban anomalies is also observed where the anomalous trend for the urban areas with population density over 3000 km^{-2} or urban surface coverage over 50%, is about 0.1 °C/decade. For less urbanized sites with population density of ≈100 km^{-2} or urban surface coverage of ≈0.05, there is an anomalous trend of 0.03–0.05 °C/decade, namely 0.3–0.5 °C/century. Similarly, other studies revealed that at the global scale, combined urban and non-urban trends of maximum and minimum temperature are about 0.1°C per 100 years higher as compared to the trends of non-urban observing stations (Easterling et al., 1997).

As in many other developing countries, since the 1980s, Pakistan has experienced higher urbanization in different parts of the country. Major cities such as Karachi (Sajjad et al., 2010), Lahore (Sajjad et al., 2009), and Faisalabad have expanded faster, and many old towns have now become prominent urban centers. Currently, almost 40% of the total population lives in cities (Fig. 1) and the rest in rural areas. According to an estimate by UNDESA (2011), almost 60% of the total population will be living in urban areas in 2050. Medium- and small sized cities, of which there are many, have grown at an even higher rate. Due to the rapid growth of cities (small, medium, and large), half of the total population is projected to live in urban areas by 2030 (Arif and Hamid, 2009). The rapid urbanization has caused rapid changes in land use and increased environmental degradation.

Figure 1

The present study quantifies the increase in temperature at several locations in Pakistan, including stations located in different types of settlements such as mega cities (urban), smaller cities (town), and rural areas, and discusses the trends on minimum and maximum temperatures as a function of the size and locations of the cities. The major focus is on the estimation of local increase of temperature to highlight the local responsibilities compared to global effects. The results are discussed using the location of the stations and their physiographic features that may have introduced specific changes in the observed time series or anomalies for certain locations.

The data source, length, and data analysis method are presented in section 2. Results are discussed in section 3. Finally, concluding remarks are provided in section 4.

2. Data and methodology

This section describes the meteorological data collected in different parts of Pakistan, their homogenization, and statistical treatment.

2.1 Meteorological data

Based on data from 36 meteorological stations including urban (16), town (11), and rural (9) stations located in different parts of Pakistan (Fig. 2), temperature data of daily minimum (T_n) and maximum (T_x) averaged on a monthly basis from 1950 to 2013 were obtained from the Pakistan Meteorological Department (PMD). To measure the temporal intensity of change in temperature, the data was first analysed as a whole data set with no distinctions between stations. Breaks in trends were identified using the SeqMK method at several years depending on the station with few breaks noted around 1980 (see section 2.4 for methodology and 3.2 for results). First, to simplify the analysis, the data set was split into two different periods as per other regions of the world (e.g., Kalnay and Cai (2003), Chung et al. (2004), or Cueto et al. (2009)): 1950–1981 (P1) and 1982–2013 (P2) for all stations and was analyzed separately for both phases of 32 years each. The temperature data are split into two different periods to determine the per decade changes of annual minimum and maximum temperatures (dT_n^a and dT_x^a, respectively) during the low urbanization period (P1) and the high urbanization period (P2) in Pakistan.

The data were also averaged on seasonal and annual basis. The characteristics of all meteorological stations including international codes, complete name, latitude, longitude, elevation, total population density of population, and date range of available data are presented in Table 1. The data of different stations were classified into three categories: urban, town and rural stations. The distinction between the urban and the rural locations is not yet amenable to a single definition that would be applicable to all countries or even to the countries within a region. In many industrialized countries, the principal difference between urban and rural areas in terms of the circumstances of living tends to be related to the degree of concentration of population (United Nations, 2018b). But it is hard to follow a single definition even for population density to distinguish between different categories of stations. As for different countries, the population size and density are not the only rule to distinguish among different categories of settlements (UK Parliament, 2018; Jones, 2002; Pizzoli and Gang, 2007; Bibby and Shepherd, 2004). Other studies use night light observations via satellite to classify monitoring stations (Imhoff et al., 1997; Hansen et al., 2001). However, this type of method cannot be homogeneously used for classification of the stations into different categories as they are located in less developed areas of the world that are facing massive energy shortages.

Figure 2

For the current study, the classification of stations into urban, town, and rural was made by following the traditional method based on population density and size, surface characteristics (paved or natural land cover) and position of the station (within populated area, outside of characteristic urban area, or in rural type landscape even located nearby cities or small towns).

The stations where there is a population density of more than 4000 persons/km^2 are considered as urban, and those where the population density is between 2000 to 4000 persons/km^2 and less than 2000 persons/km^2 are considered as town and rural, respectively.

2.2 Test for homogeneity of data

Several non-climatic factors such as station relocation, changes in instruments, screen of the instrument, observation timings, surrounding areas, observational procedure, calculation procedures and instrumental inaccuracies, observer capability, attentiveness, and observing regulations cause the inhomogeneities in time series data. Such non-climatic factors hide the real signal of CC during one specific period (Aguilar et al., 2003). While they may have provided valuable information on the immediate surroundings of stations (typically metadata within tens of meters help to better understand the local effect), the detailed metadata of the stations could not be obtained from the data source. To control the quality and remove inhomogeneities from the time series data, HOMER version 2.6, which includes tools for quality control, homogenization (detection and adjustment), and visualization of monthly climate network, is used. Based on relative techniques, it combines different detection approaches: pairwise detection (based on multiple-comparisons of station pairs), joint detection (based on simultaneous statistical modeling of a station network), and traditional weighted references. HOMER applies an ANOVA model for simultaneous adjustments of detected and validated breaks (Osadchyi et al., 2018; Freitas et al., 2013; Mestre et al., 2013). HOMER has been constructed exploiting the best characteristics of some other state-of-the-art homogenization methods, that is, PRODIGE, ACMANT, and CLIMATOL (Mestre et al., 2013).

Table 1

To avoid any bias of urban area's temperatures on non-urban stations over homogenized data series, the homogeneity of the data was checked for urban and non-urban stations separately. We used HOMER without any development, modification, addition, or deletion. The procedure follows the preparation of files for network numbers, selection of parameter (temperature, precipitation), unit of parameter (°C), selection of correlation for interactive option with Pearson's-r value of 0.99 with correlation of eight neighboring stations for comparison. Annual and seasonal pairwise detection with visualization of series was performed for the homogenization process.

Figure 3

For the fast quality control, for the detection of any major errors in the data, the fast CLIMATOL command was used. Data were then quality controlled followed by the detection and removal of outliers within time series data in comparison with other neighboring stations. For homogenization, pairwise and joint detection were performed and data were then corrected using the "correction" option to obtain the homogenized data series for further analysis. For the statistical procedure and HOMER's source code, see Osadchyi et al. (2018), Freitas et al. (2013), and Mestre et al. (2013), and the HOMER manual on http://www.homogenisation.org/homer.2.6.R, which explains the installation, sourcing of HOMER, preparation of the computer, and communication with the software.

Figure 3 highlights the trends of T_n^a of Lahore (Fig. 3a) and Quetta (Fig. 3b) with and without homogeneity check. It shows that after detecting and removing the outliers and inhomogeneities within the T_n time series data in comparison with other neighboring stations, the data obtained for further analysis were without biases. The adjustment value of temperature data using HOMER remained different for each station, such as 0 to 1.1 °C for Lahore and 0 to 1.9 °C for Quetta. See Mestre et al. (2013) for details of the statistical procedure and functioning of HOMER.

2.3 Temperature trends

To assess the temperature trends using the homogenized data series, anomalies dT of annual and seasonal mean of minimum (T_n) and maximum (T_x) temperatures were computed.

The linear least squares regression technique was applied to extract the following:

- Trends of annual mean of anomalies of minimum (dT_n^a) and maximum temperatures (dT_x^a), that is, the slopes of the linear variations.
- Trends of seasonal mean of dT_n^s and dT_x^s for all four seasons in Pakistan with *s* an index to indicate different seasons: autumn (s=Au), winter (s=Wi), spring (s=Sp), and summer (s=Su).
- Trend differences of dT_n^p and dT_x^p between P2 (1982–2013) and P1 (1950–1981), respectively.
- Trend of dT_n^{u-r} and dT_x^{u-r}, which represent annual and seasonal difference in anomalies of minimum and maximum temperature between urban and rural stations, respectively (Table 2).
- Assessment of trends of dT_n^{t-r} and dT_x^{t-r}, which represents annual and seasonal difference in anomalies of minimum and maximum temperature between town and rural stations, respectively.

2.4 Mann-Kendall test

The Mann-Kendall (Khambhammettu, 2005) test is used to determine whether the observations in the data tend to increase or decrease over the study period (and not only for 2 periods of time). To identify the significant change of trends in temperature data of various stations of Pakistan, the sequential Mann-Kendall (SeqMK; Mohsin and Gough, 2010) test was used.

The application of sequential Mann-Kendall test has the following steps:

1. The N values of the original data of a data series (say) *x* are replaced by their ranks in a new data series *y,* arranged in ascending order
2. The magnitudes of y_i (i = 1,...,N) are compared with y_j (j = 1,...,i-1). At each comparison, the number of cases $y_i > y_j$ need to be counted and denoted by n_i
3. A statistic t_i can be defined as follows:

   $t_i = \sum_i n_i$
4. The distribution of the test statistic has an expectation mean $E(t_i)$ and a variance as

   $E(t_i) = i(i - 1)/4$

   and $var(t_i) = i(i — 1)(2i + 5)/72$
5. The sequential values of the statistic $u(t_i)$ can then be computed as

   $u(t_i) = [t_i — E(t_i)] / SQRT(var(t_i))$
6. Here, $u(t_i)$ is a standardized variable that has zero mean and unit standard deviation. Therefore, its sequential behavior fluctuates around zero.
7. The values of $u'(t_i)$ can be computed backward in a similar manner as the forward series but starting from the end of the series.
8. $u(t_i)$ and $u'(t_i)$ can be plotted to detect the systematic change in climate data (Sneyers, 1990). The "systematic change" refers to any change in the time series data that represents sustained changes for the area under investigation. In the case of a significant trend, the graphical representation of u(t) and u'(t) curves identifies (at the intersection) the start of the systematic

change in the time series. In the absence of any statistically significant trend, the curves usually overlap several times toward the end of the time series.

The normalized values of the test statistic, $u(t_i)$, are also used to test the null hypothesis in favor of the existence of a trend through the p-value. When the p-value is lower than 0.01, there is a strong significance in favor of a trend. When the p-value is greater than 0.01 but below 0.05, there is a significance in favor of a trend, but when it is greater than 0.05, the potential trend is not significant.

More information on this procedure can be obtained from the WMO paper by Sneyers (1990).

3. Results

3.1 Temperature trends

The summary of the results reported in Table 2 highlights the dT_n and dT_x during P1 and P2 on an annual and a seasonal basis at urban, town, and rural stations. To assess the long-term UHI, Table 2 also highlights the long-term temperature differences between urban and rural stations ($dT_n^{u\text{-}r}$ and $dT_x^{u\text{-}r}$) and between town and rural stations ($dT_n^{t\text{-}r}$ and $dT_x^{t\text{-}r}$) calculated by taking the average of annual and seasonal dT_n and dT_x of all urban, town, and rural stations separately. General assessment of the results reveals:

- During P1, there were increasing trends in T_n^a at urban, town, and rural stations, but there are decreasing trends in T_x^a only at urban and town stations.
- During P2, there were increasing trends in T_n^a and T_x^a at all types of settlements, that is, urban, town, and rural stations.
- During P2, dT_n^a and dT_n^s were observed significantly higher at urban stations than town and rural stations.
- During P1, the per decade trends of dT_n^a at urban, town, and rural stations were 0.04°C, 0.13°C, and 0.20°C, respectively.
- During P2, the per decade trends of dT_n^a at urban, town and rural stations were 0.37°C, 0.10°C, and 0.03°C, respectively.
- The trend of dT_n^a during P2 at urban stations was significantly higher than the dT_n^a during P1 (0.37°C/decade vs 0.04°C/decade, respectively).
- Among all the seasons, spring is highly affected by changes in which minimum and maximum temperatures at urban, town, and rural stations increased more than any other season.
- Long-term annual net change in trend of $dT_n^{u\text{-}r}$ is 0.50°C/decade, which is the highest in spring (0.62°C/decade).
- Long-term annual net change in trend of $dT_x^{u\text{-}r}$ is only 0.03°C/decade, which is the highest in spring (0.42°C/decade).

Figure 4 illustrates the details of the results, showing the annual net change in trends of dT_x^a as a function of the annual net change in trends of dT_n^a on all the 16 urban, 11 towns, and 9 rural stations for both periods.

The results indicate that not all the stations display positive trends; a number of stations also show negative temperature trends. However, maximum and minimum temperatures have increased at most stations, especially in P2 (Fig. 4a and 4b). Figure 4a reveals that during P1, there is significant variation in trends of dT_n^a and dT_x^a at individual urban, town, and rural stations. Panjgur is one of the town stations, which showed an irregular trend for dT_n^a compared to its neighboring stations and other stations of the same category. Faisalabad and Gilgit are two urban stations, but the both show negative dT_n^a during P1 with -0.46°C^{-dec} and -0.30°C^{-dec}, respectively.

Figure 4(b) indicates that most of the urban stations show increasing dT_n^a and dT_x^a during P2, with the minimum temperature showing higher increasing tendency than the maximum temperature. The average dT_n^a trend of all urban stations is also much higher than at town and rural stations, while the average dT_x^a trends at rural, urban, and town stations are similar. The temperature difference, especially at urban stations, (Figure 4(c)) highlights the effect of rapid urbanization in recent decades. Most of the urban stations except Hyderabad show the higher increasing shift in dT_n^a and dT_x^a where it is larger for dT_n^a.

Figures 5(a) and 5(b) highlight the comparison of changing order of stations based on dT_n^a for P1 and P2. Overall analysis reveals that the variation in temperature depends not only on rate of urbanization; there may be many other factors that can affect the temperature trends of a particular place. This fact is evident as among all the data series, dT_n^a at Panjgur (a town station) during P1 increased more rapidly than any other station. The figure highlights that there were only two out of a total 36 stations where dT_n^a is more than 0.50°C^{-dec} during P1. During P2, the number of stations where dT_n^a is more than 0.50°C^{-dec} reached to nine stations (Table 3). It is therefore evident that temperature at urban stations increased faster in recent decades. Figures 6(a) and 6(b) explain that dT_x^a is higher at more stations during P2 than P1. There are some urban stations where dT_n^a increased, however dT_x^a is higher mostly at rural and town stations.

Figure 7 illustrates the geographical distributions of stations' linear changes of dT_x^a (top) and dT_n^a (bottom) for P1 and P2 over the entire period (32 years for each period). Night warming during P2 is higher at number of stations mainly situated in Indus valley area where several major cities are located near to one another such as Sialkot, Jhelum, Lahore, Faisalabad, Sargodha, Multan, and Bahawalpur. Most of these cities are located on flat land on the Indus plain. The maps highlight that day warming is substantial mostly at stations in northern mountain areas, which are a major source of fresh water for large parts of the country. The rise in maximum temperature at stations in northern areas indicates an alert which may affect the precipitation pattern and may also accelerate the retreat of glaciers in the northern highlands, which are considered as the lifeline of Pakistan. Other studies have also found that mountain regions are warming faster than the global or hemispheric average (Beniston et al., 1997; Liu and Chen 2000; Ceppi et al., 2010).

Table 2

Figure 4

Figure 5

Figure 6

Figure 7

The percentage of stations out of the total number of stations where annual and seasonal minimum and maximum temperature showed positive trends/increased is reported in Table 4. It reflects that during P2, at almost 94% of urban stations, dT_n^a and dT_n^s were positive while this was only 51% during P1. Further details for town and rural stations are also presented in Table 4.

Table 3

Table 4

Figure 8

Figure 8 describes the magnitude of urban warming in comparison of urban station to its surrounding rural station or smaller town. Figure 8a highlights the trends of dT_n^a over Quetta, an urban station, and Kalat, a nearby rural station. Over a period of 64 years, long-term annual increase in trends of dT_n^a over Quetta city are found up to 0.25 °C-dec more than that of Kalat. Figure 8b highlights the trends of dT_n^a over Karachi, the largest city in Pakistan, and Lasbella, a nearby town station. The long-term annual increase in trends of dT_n^a for Karachi are up to 0.011 °C-dec more than the nearby smaller town. These two comparisons reveal that there is substantial urban impact on rising temperature trends. These types of trends are similar for many other stations in other parts of the world (Brunetti et al., 2000; Liu et al., 2007) as well as in Pakistan when urban and rural and urban and town stations are compared.

3.2 Results from SeqMK test

The SeqMK test is used to detail the changes in time series data of maximum and minimum temperature (not only for 2 periods in section 3.1, but also over the entire period), station by station to identify specific features. It provides new information compared to the HOMER method, which only allows us to detect and correct changes mainly concerning the station itself (change of instruments or localization). Here, we evaluate the possibility to automatically detect significant changes in the trends due to CC, urbanization, or other local land use change. For all stations, two types of information are presented:

- The years for which a break of trend is observed. Indeed, in cases where the forward and the backward $u(t_i)$ and $u'(t_i)$ series intersect, we note the associated years as breaks in the trends. If they intersect several times in a short period, we do not consider these changes as significant. Figures 9, 10 and 11illustrate specific examples for urban, town, and rural stations, respectively. Islamabad is an example for which both maximum and minimum temperatures show statistically significant abrupt change in trend, whereas Karachi-AP shows no well-defined commencement of such abrupt changes for maximum and minimum temperatures. Sialkot has a strong increase of minimum temperatures while these results are not considered significant. This result indicates a strong time variability around the trend.
- The significance of the observed trends using the p-value.

Considering the results from the previous section on trend analysis, we expect to see systematic changes mostly in the minimum temperature due to the expansion of urbanization in urban areas compared to the town and rural areas.

Figure 9

Figure 10

Figure 11

Table 5 shows that for all urban stations except Peshawar, Bahawalpur, D.I. Kahn, and Faisalabad, the SeqMk methodology detects statistically significant trends (p-value<0.05) for either the maximum or the minimum temperatures, or both. It is noted that half of breaks detected in T_n trends are between 1975 and 1985, while breaks in T_x appear at any time, but mostly late 1960s/early 1970s, and late 1990s/early 2000s. The SeqMk method suggests progressive trends of T_n temperatures at most urban stations over the entire period, while most of these stations showed quite high increases in T_n temperatures between P1 (before 1981) and P2 (after 1981) (see section 3.1). One can cite the example of Lahore where no abrupt changes of trend in T_n are observed by the SeqMk, but the trend for dT_n^a during P1 (urban) is 0.27 °C/decade and 0.73 °C/decade for P2. Karachi and Hyderabad are two urban areas situated near the sea with green surrounding areas and show significant abrupt changes in maximum temperature trends in the late 1970s/early 1980s. Islamabad shows a break in trends for T_n and T_x in the late 1990s.

Table 5

Table 5 also shows the SeqMk methodology detects statistically significant trends (p-value<0.05) for either the maximum or the minimum temperatures, or both for all town stations except Sibbi. Only five out of 11 town stations showed statistically significant trends in T_n. However, eight town stations show statistically significant trends (MK-test) in T_x, with several breaks detected between 1965–1975, the 1980s and late 1990s.

The results of SeqMK test for the rural stations should be analyzed differently, since the abrupt changes cannot be due to urbanization (i.e. the stations are far away from urban areas). The changes in the rural location can only be explained by changes in climate or the surface characteristics. We note that for all rural stations, except Kalat, the detected trends are statistically significant (p-value<0.05) for either the maximum or the minimum temperatures, or both. We notice a slight increase of breaks since the 1980s.

4. Discussion and Conclusions

Both local and global warming make cities more vulnerable in terms of local extremes such as heat waves, which, in extreme conditions, aggravate the mortality rate mainly among children and the elderly. This study explored the variation in temperature over major cities, town areas, and at rural stations in Pakistan. Using the data of 36 meteorological stations with different physical characteristics (urban, town, and rural), the results of each type of station were not uniform and there were significant variations in temperature trends even among stations of the same category, that is, urban or rural stations.

It was observed that, on average, minimum and maximum temperature increased at all types of stations, but not at all stations. We show that the effect of urbanization is more pronounced on the minimum temperature than the maximum temperature and more at urban stations than town and rural stations. This is evident from the trends of averaged annual T_n of all urban stations, which are higher than the average annual T_n of rural stations (0.37°C^{-dec} vs 0.03 °C^{-dec}, respectively). The strength of warming over urban areas signifies alarming changes in the climate of urban areas.

Thus, the present study confirms the general notion that the larger the city, the greater its impact on local warming (Hung et al., 2006). However, based on our findings, it can also be asserted that larger cities' minimum or maximum temperatures do not necessarily increase more than those of smaller cities. It was found that even in the recent period (P2), dT_n or dT_x at different urban stations were not ranked according to the size of the cities (Figure 5b and Table 1). This may be influenced by other factors present in or around the individual urban stations, such as very local effects (impact of vegetation or specific urban structures), elevation, relief, or latitude; this needs to be evaluated by developing different scenarios to find this type of cause of change in temperature.

As the topography of Pakistan is not uniform, it is unsurprising that there are not uniform characteristics of dT_n and dT_x at all sets of stations (urban, town, and rural sets) or even a single set of stations. The observed dT_n or dT_x of nearby stations may also differ in ways that are unexpected in view of the classifications of the sites. For example, Hyderabad is an urban station that is larger than Chhor, a nearby town station. Both stations are located in the same type of environment; however, T_n at Hyderabad has decreased whereas it has increased at Chhor. Similarly, Gilgit (urban station) and Bunji (rural station) are located in the same kind of environmental conditions, at almost the same altitude and have the same type of topography (mountainous). However, this study revealed that during recent decades, the rise in T_n at Gilgit is substantially lower than Bunji even though the former is an urban station and larger in size than the latter. On the other hand, T_x at Gilgit increased more than at Bunji.

Although a majority of studies suggest that warming is more rapid at higher elevation which is substantial in dT_n^a of P1 and dT_x^a of P2 of the present study, a number of studies show either no relationship or a more complex situation. A majority of studies also suggest that minimum temperatures show a stronger tendency toward elevation-dependent warming (EDW) than maximum temperatures (Pepin et al., 2015). In certain cases, it may be true but not in others. It is also important that rising temperatures at stations located in northern parts of Pakistan, containing major glaciers, may definitely lead to retreat of glaciers at higher elevations as the overall climate system is warming. As a result of local/regional warming such as in the Tibetan/Himalaya region, the snow cover season has shortened and more precipitation is now falling as rain (Rikiishi and Nakasato, 2006; Archer and Fowler, 2004; Bhutiyani et al., 2010).

Thus, it can be concluded that the trends of dT_n and dT_x are strongly influenced by the local conditions where a particular station is located. Local characteristics of different stations, even with similar terrain, population density, elevation, and mountain valley shape where a station is located, greatly affect the dT_n and dT_x and should be detailed as metadata. The orographic climatic conditions, nearness to sea, and flat areas also affect the local area temperature. Differing influences on dT_n and dT_x are evident from other regional cities of India where at Mumbai's annual dT_n shows decreasing trends while dT_x shows increasing tendencies. Similarly, annual dT_n at Kolkata shows lower trends than annual dT_x (Dhorde et al., 2009).

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TEMPERATURE VARIABILITY OVER URBAN, TOWN AND RURAL AREAS: THE CASE OF PAKISTAN

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Figures

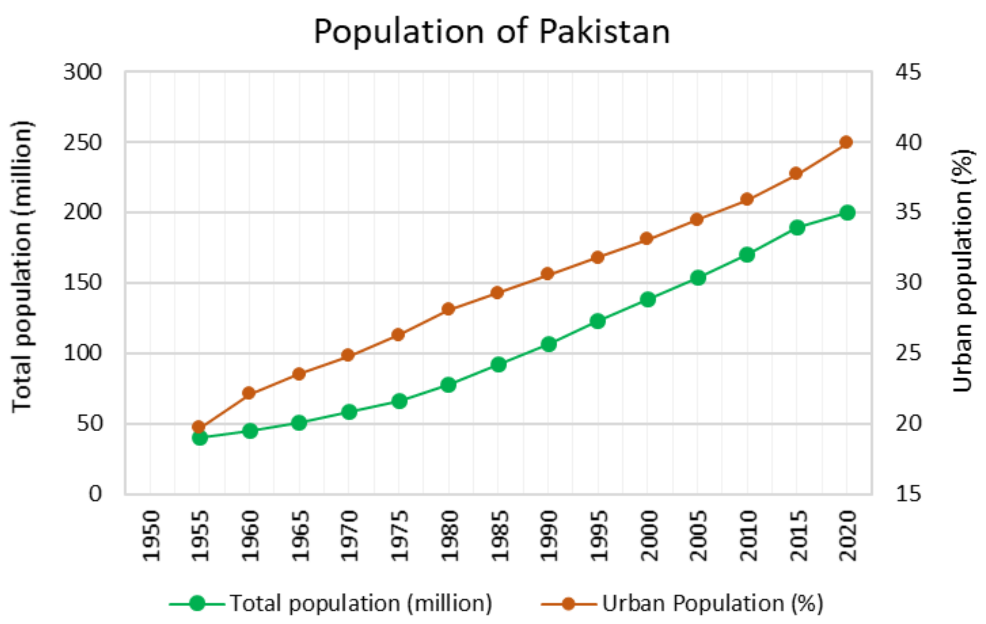

Figure 1: Total population (million) and total urban population (%) of Pakistan for the period 1955 – 2020.

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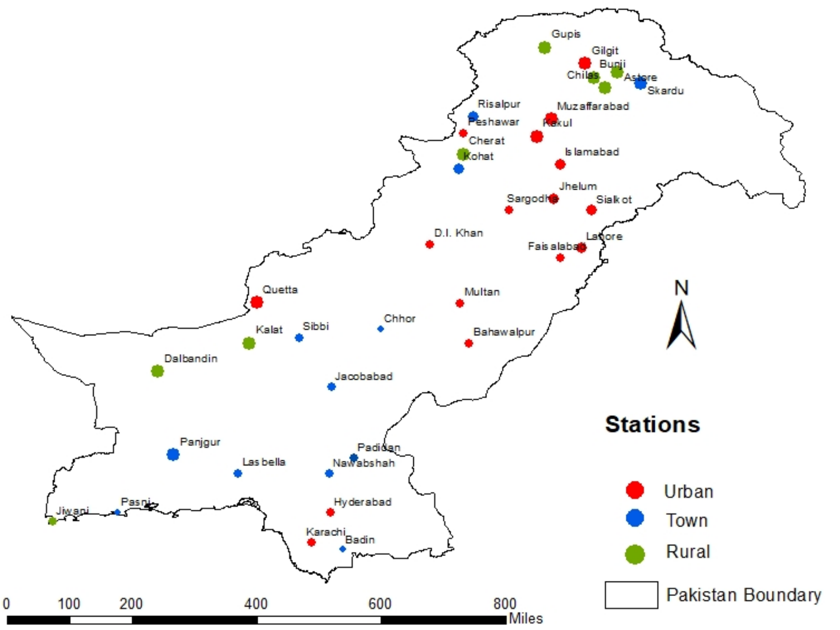

Figure 2: Location map of network of meteorological stations of Pakistan. Large circles represent the stations located at higher altitude and small circles the stations at lower altitude..

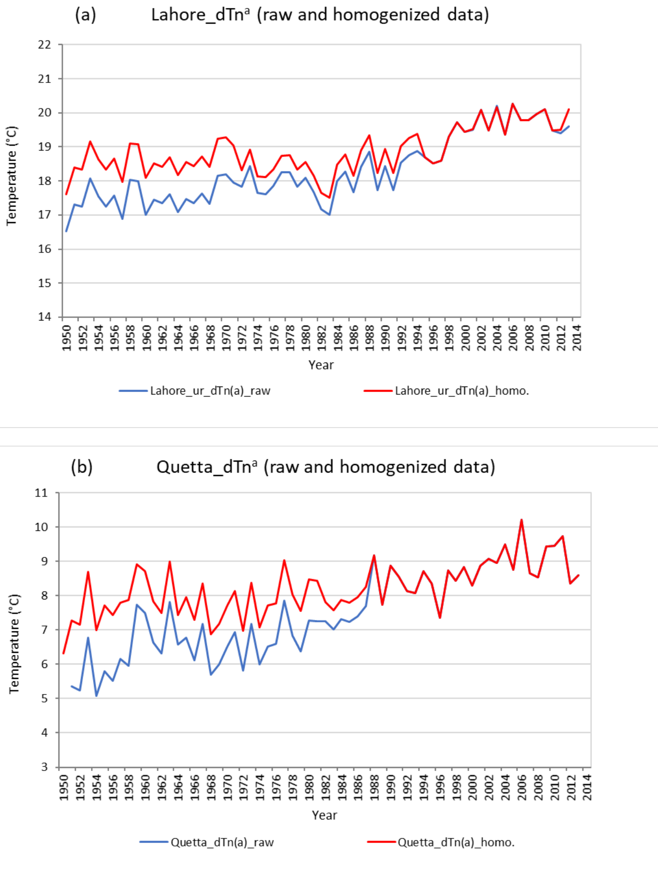

Figure 3: Comparison of trends of T_n^a with and without the homogeneity check for Lahore (a) and Quetta (b).

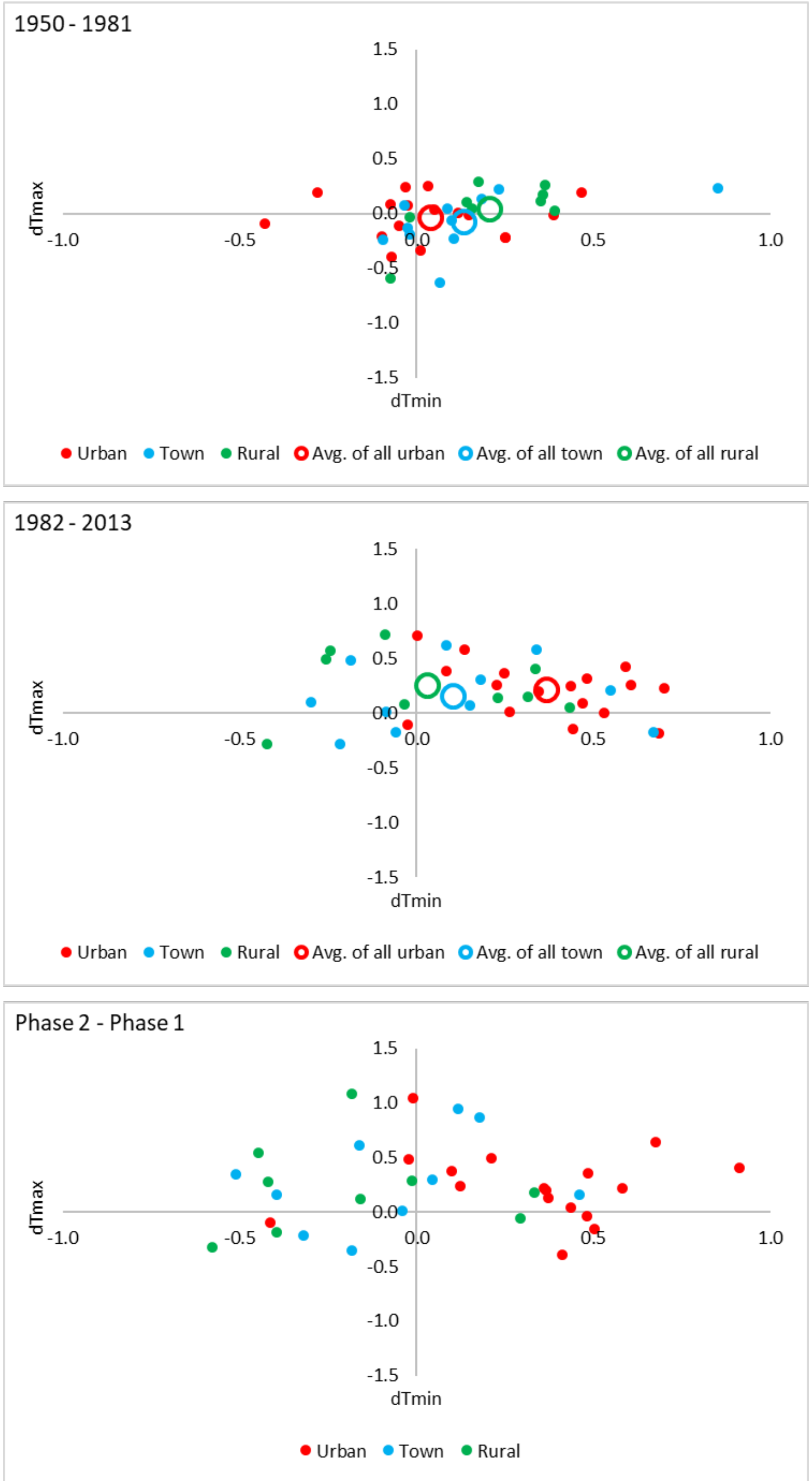

Figure 4: Per decade change in trends of dT_n^a (x-axis) as a function of trends of dT_x^a (y-axis) for urban (red filled circles), town (blue filled circles) and rural (green filled circles) stations for P1 (a); P2 (b) and dT_{P2-P1} (c). The hollow red, blue and green circles in *a (P1)* and *b* (P2) represent the trends of dT_n^a as a function of trends of dT_x^a drawn by taking the mean of all urban, town and rural stations, individually, respectively.

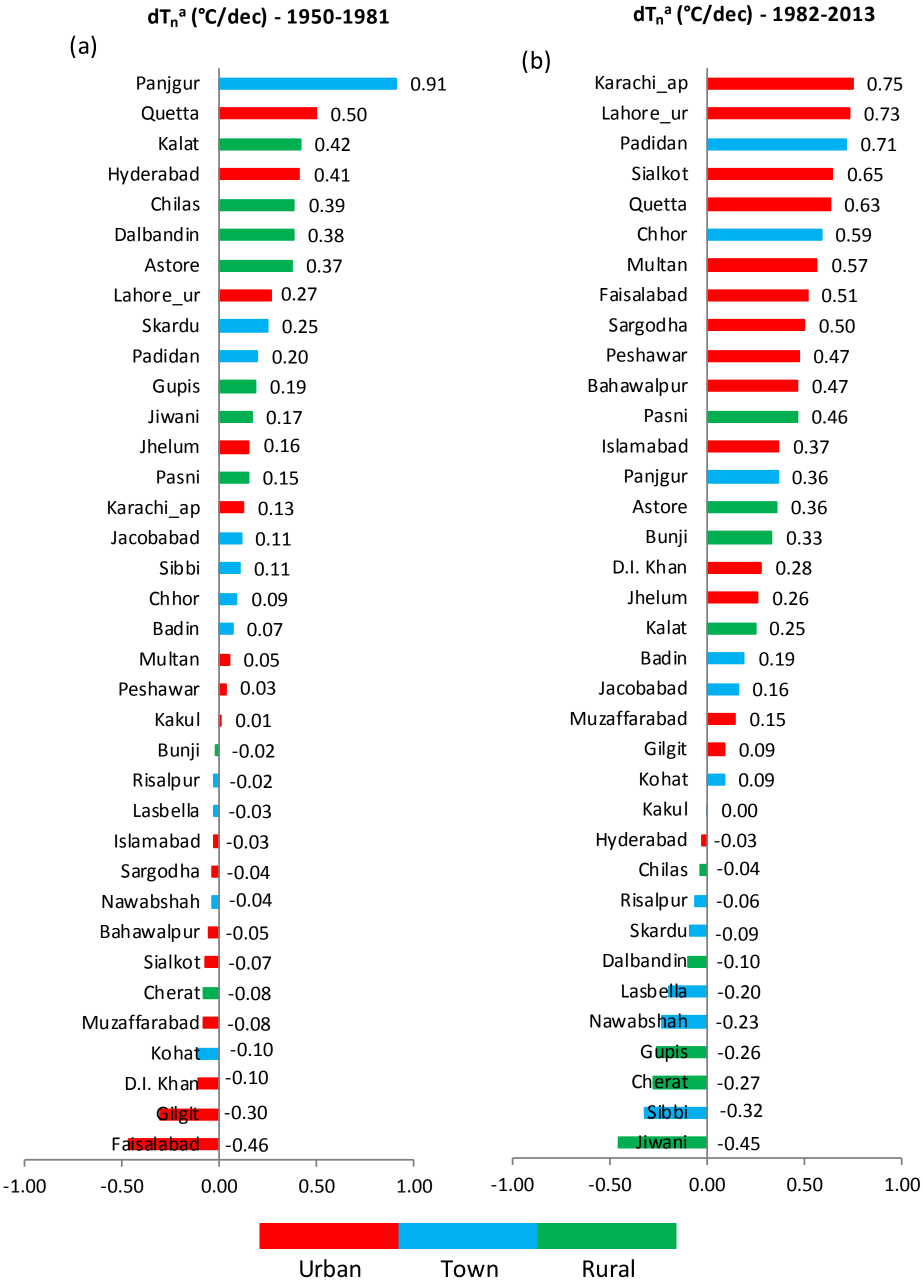

Figure 5: Observed trends of dT_n^a (°C^{-dec}) of different stations of Pakistan for P1 (a) and P2 (b).

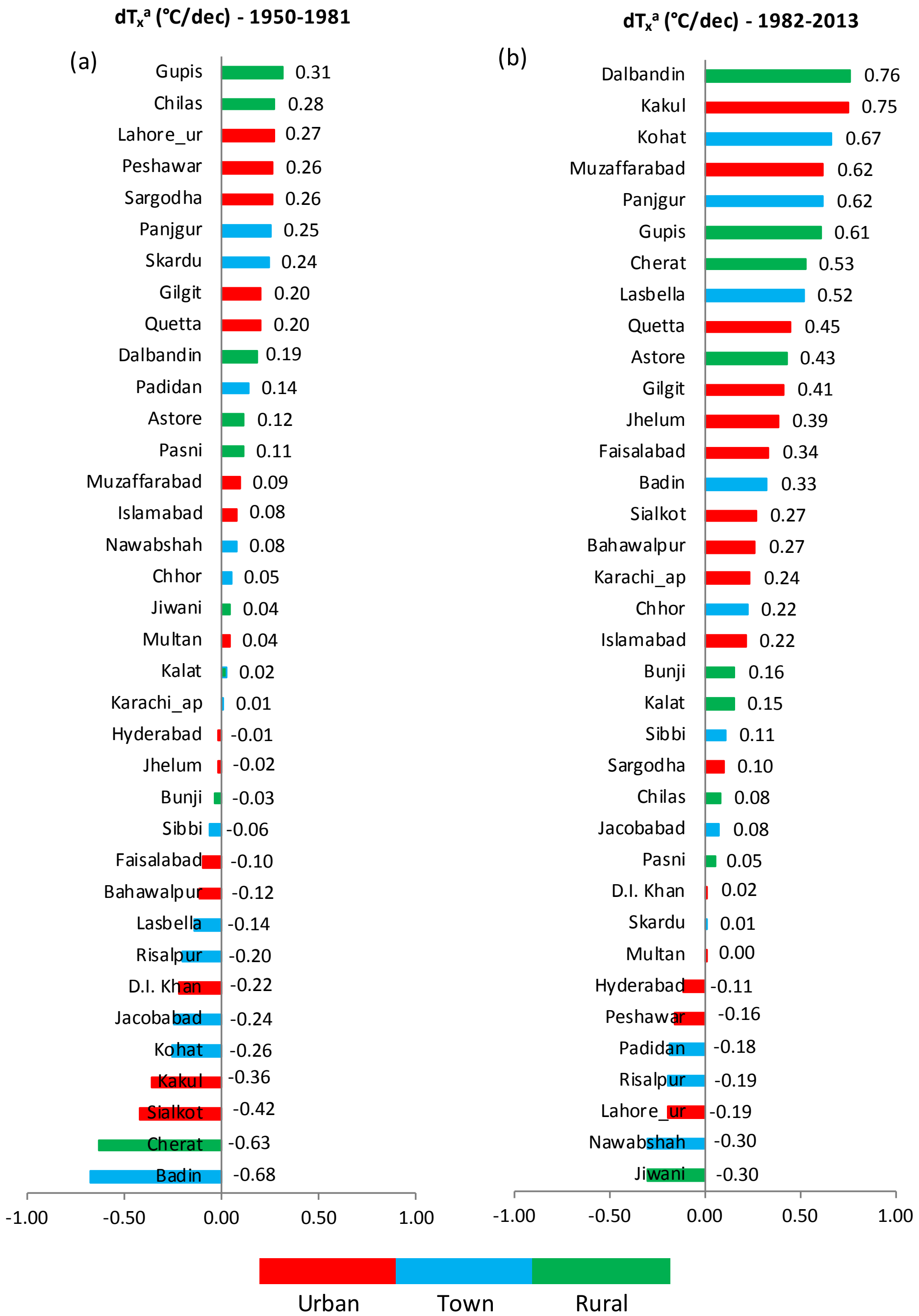

Figure 6: Observed trends of dT_x^a (°C^{-dec}) of different stations of Pakistan for (a) P1 and (b) P2.

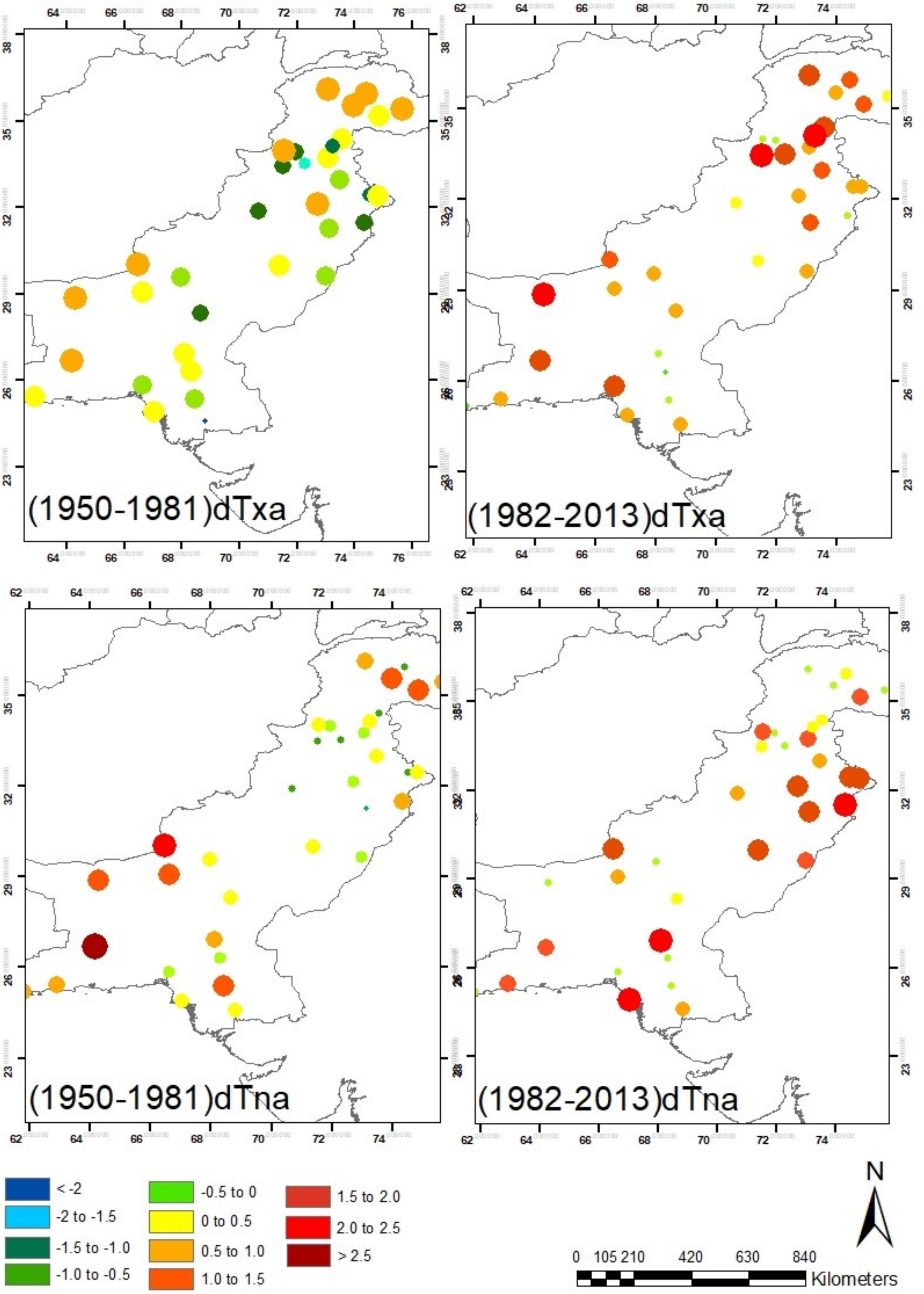

Figure 7: Graphical presentation of linear changes in dT_x^a (top) and dT_n^a (bottom) of all stations for each of P1 and P2 (32 years for each period).

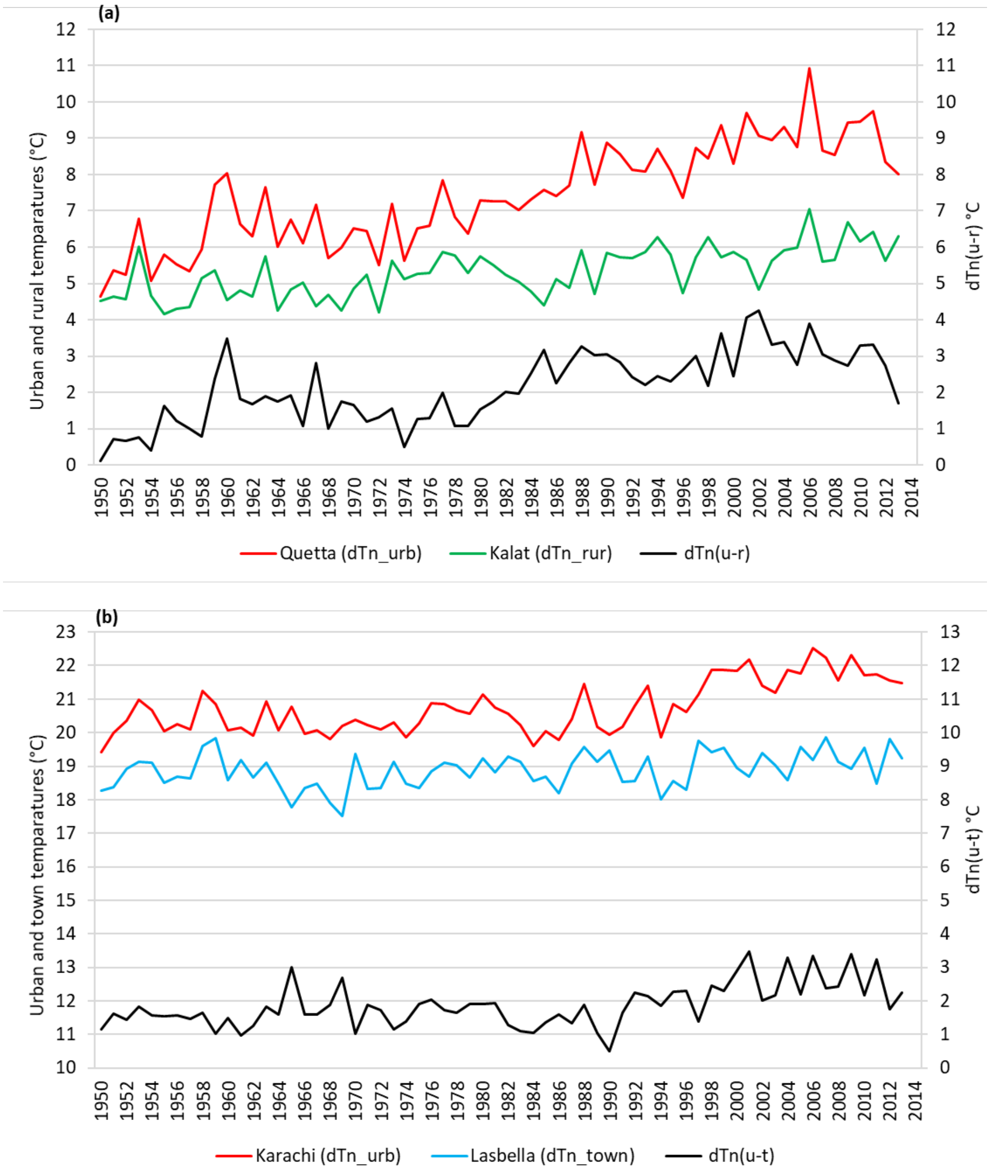

Figure 8: Magnitude of urban warming in comparison of *(a)* Quetta (urban) vs Kalat (rural) and *(b)* Karachi (urban) vs Lasbella (town).

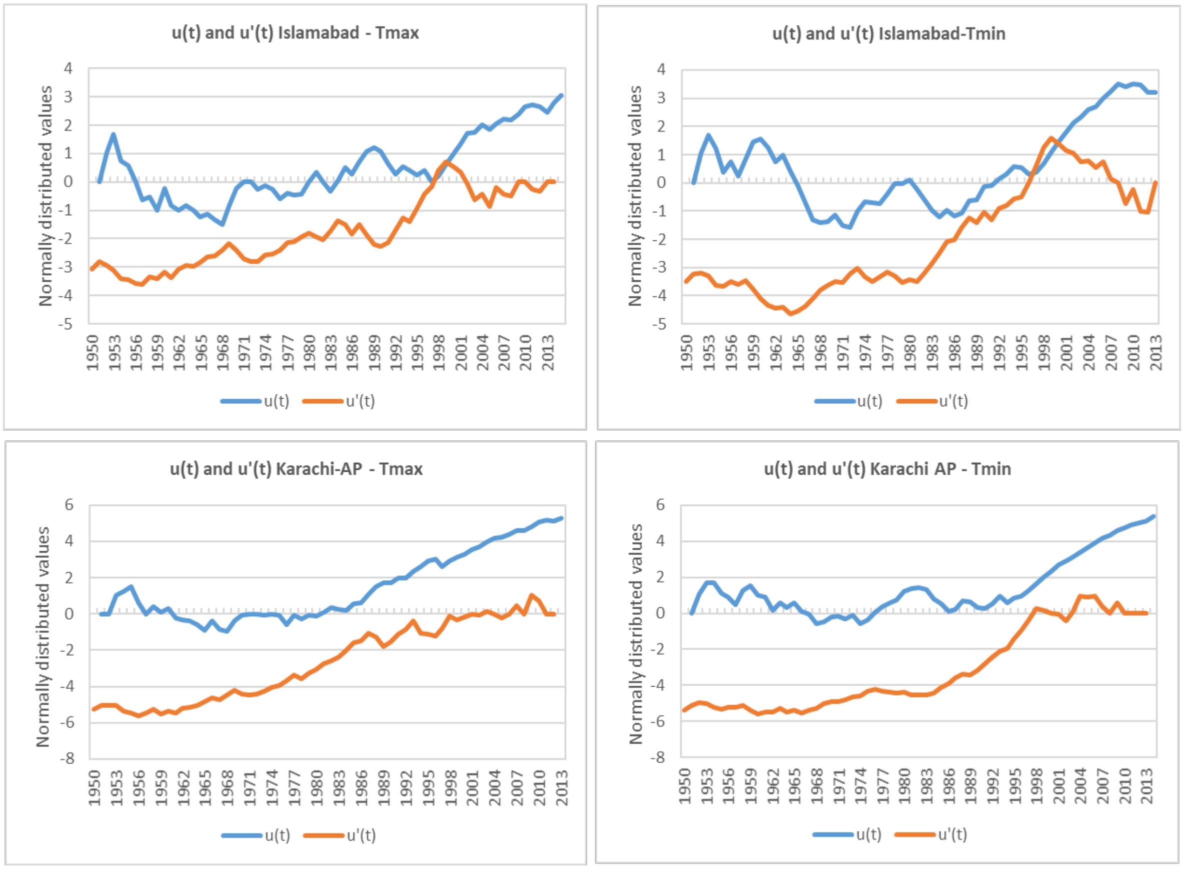

Figure 9: Sample plots showing the changes for urban stations associated with u(t) and u'(t), that is, the forward and backward time series, respectively obtained from the SeqMK test.

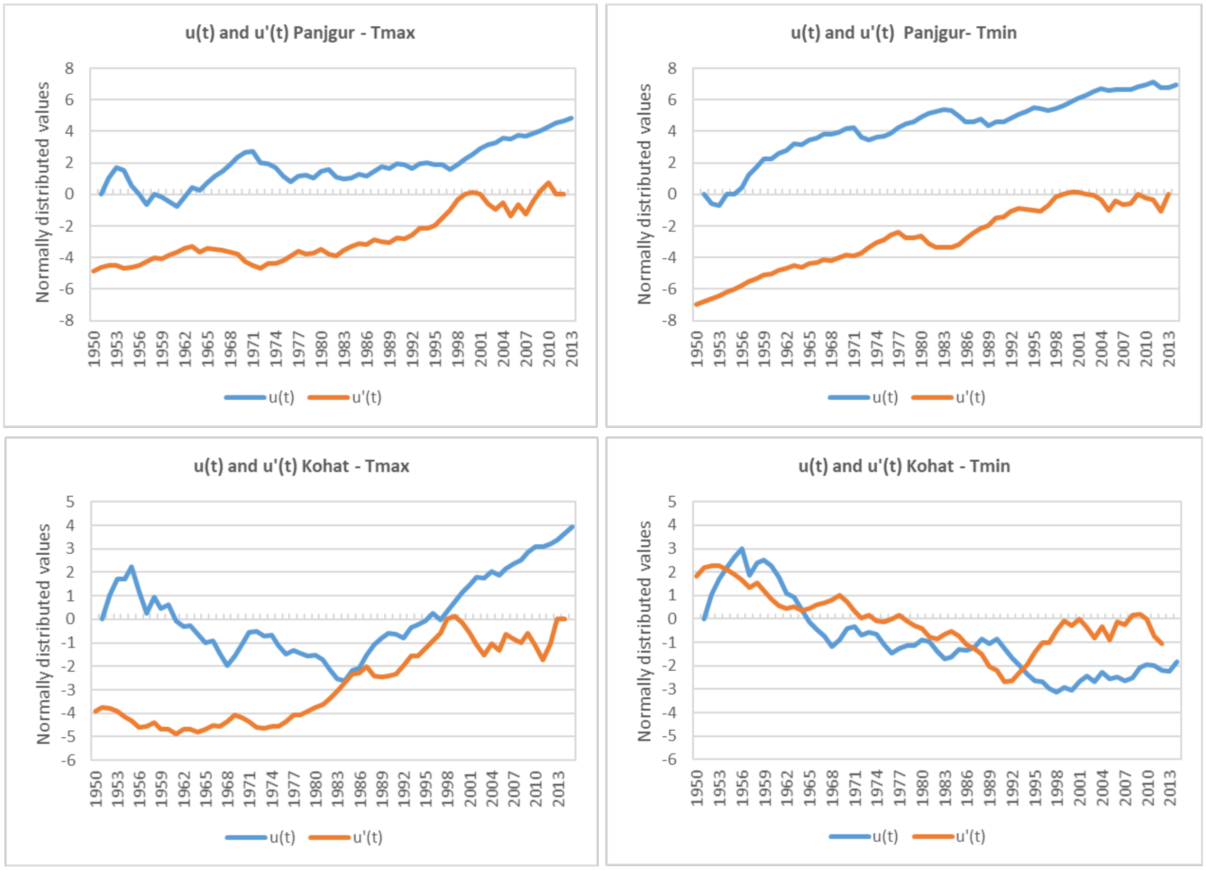

Figure 10: Sample plots showing the changes for town stations associated with u(t) and u'(t), that is, the forward and backward time series, respectively obtained from the SeqMK test.

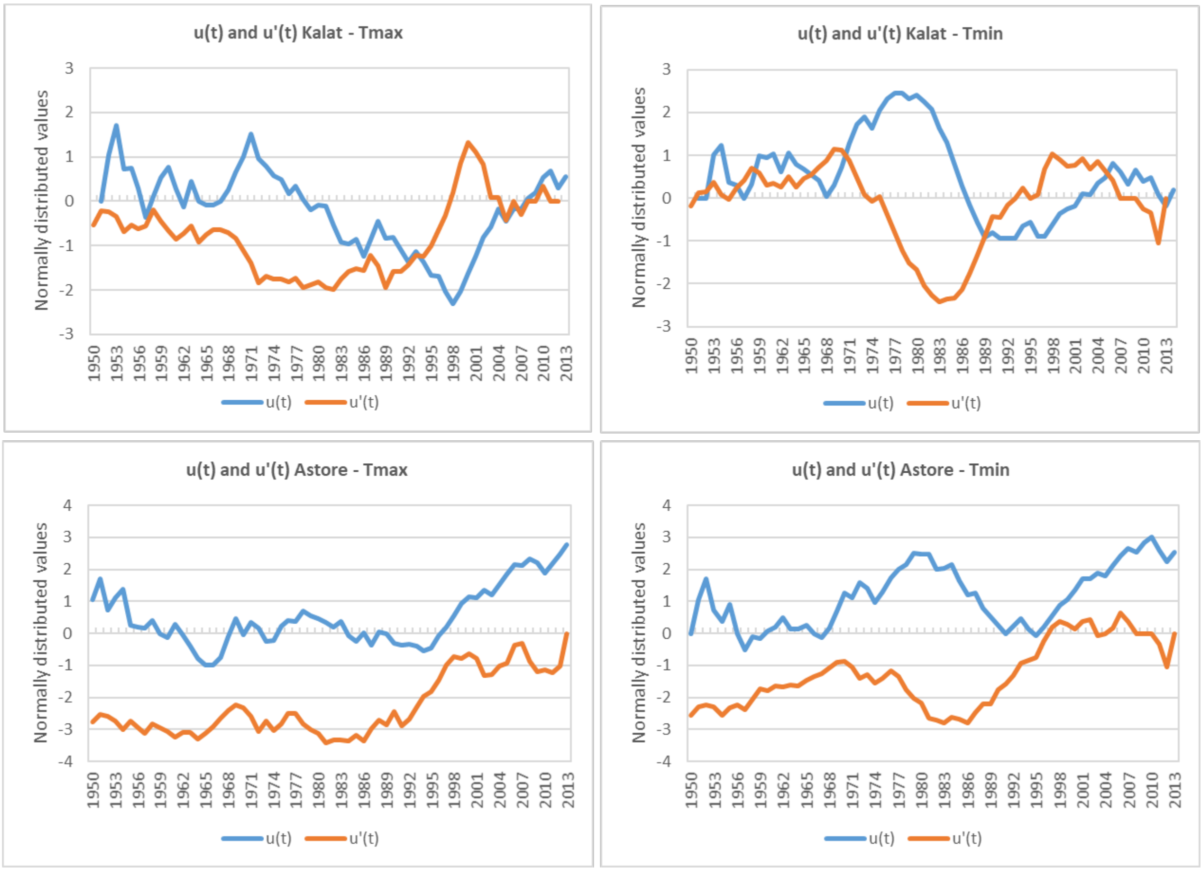

Figure 11: Sample plots showing the changes for rural stations associated with u(t) and u'(t), that is, the forward and backward time series, respectively obtained from the SeqMK test.

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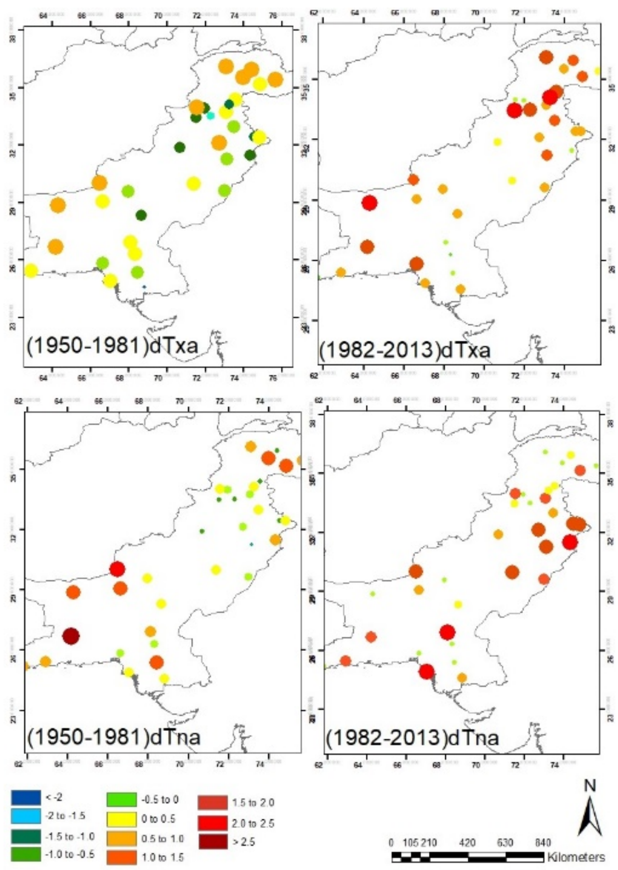

This study focused on temperature trends in urban, town and rural stations of Pakistan. It was observed that minimum and maximum temperature increased on average at all kinds of stations, though not at every station. The effect of urbanization is more pronounced on the minimum temperature rather than the maximum temperature and more at urban stations than the town and rural stations. This is evident from the obtained trends of averaged annual T_n of all urban stations which are many times higher than the average annual T_n of rural stations (0.37°C^{-dec} vs 0.03°C^{-dec}, respectively in 1982-2013). The predominance of warming over urban areas signifies alarming changes in urban climate. The study also revealed that the rate of increase in minimum temperature based on data analysis from 1982-2013 at urban stations is significantly higher than in the smaller towns." Minimum temperature is especially increasing in the big cities in the Indus valley where more than half of the population of Pakistan lives.

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Tables

Table 1: Geographical description of meteorological stations located in different parts of Pakistan.

Sr. No	Station description		Geographical location			Geographical conditions				Data available
	Name	WMO Code	Latitude	Longitude	Elevation (m)	Total population	Population density (Km-2)	Area (km-2)	Station type	
Urban (density > 4000 persons/sq.km)	Gilgit	41516	35.55	74.2	1460	209000	5061	41	Urban	1950-2013
	Peshawar	41530	34.1	71.35	360	1970000	11205	176	Urban	1950-2013
	Muzaffarabad	41532	34.22	73.29	2300.9	136700	6355	22	Urban	1950-2013
	Islamabad	41571	33.37	73.6	508.1	1015150	4893	207	Urban	1950-2013
	Sargodha	41594	32.3	72.4	188.1	660000	12022	55	Urban	1950-2013
	Jhelum	41598	32.56	73.44	287.1	190425	8463	23	Urban	1950-2013
	Sialkot	41600	32.31	74.32	255.1	655852	7158	92	Urban	1950-2013
	D.I. Khan	41624	31.49	70.56	171.2	217457	5436	40	Urban	1950-2013
	Faisalabad	41630	31.26	73.8	185.6	3204726	14982	214	Urban	1950-2013
	Lahore_ur	41640	31.33	74.2	214	11126285	16876	659	Urban	1950-2013
	Quetta	41660	30.15	66.53	1588.9	1001205	6620	151	Urban	1950-2013
	Multan	41675	30.12	71.26	122	2058290	10366	199	Urban	1950-2013
	Bahawalpur	41700	29.2	71.47	110	681696	9500	72	Urban	1950-2013
	Hyderabad	41764	25.23	68.25	28	1732693	5432	319	Urban	1950-2013
	Karachi	41780	24.54	67.8	21.9	14916236	19466	766	Urban	1950-2013
	Kakul	41535	34.11	73.15	1307.9	293137	7769	38	Urban	1950-2013
Town (density 2000 to 3999 persons/sq.km)	Risalpur	41533	34.4	71.59	317	37099	2027	18	Town	1950-2013
	Kohat	41564	33.34	71.26	513	151488	2375	64	Town	1950-2013
	Jacobabad	41715	28.18	68.28	54.9	170653	3778	45	Town	1950-2013
	Badin	41785	24.38	68.54	9	73572	3880	19	Town	1950-2013
	Lasbella	41742	26.14	66.1	87	156279	2517	62	Town	1950-2013
	Nawabshah	41749	26.15	68.22	37	134225	2246	60	Town	1950-2013
	Panjgur	41739	26.58	64.6	968	90324	2024	45	Town	1950-2013
	Sibbi	41697	29.33	67.53	132.9	64096	3859	17	Town	1950-2013
	Chhor	41685	29.53	69.43	4.9	22302	2011	11	Town	1950-2013
	Skardu	41517	35.18	75.41	2317	42642	2244	19	Town	1950-2013
	Padidan	41746	26.51	68.8	46	25355	2894	9	Town	1950-2013
Rural (density < 2000 persons/sq.km)	Gupis	41504	36.1	73.24	2155.9	8970	1357	7	Rural	1950-2013
	Bunji	41518	35.4	74.38	1372	6412	1201	5	Rural	1950-2013
	Chilas	41519	35.25	74.6	1249.1	6796	956	7	Rural	1950-2013
	Astore	41520	35.2	74.54	2168	5920	1361	4	Rural	1950-2013
	Cherat	41565	33.49	71.33	1372	2986	243	12	Rural	1950-2013
	Kalat	41696	29.2	66.35	2015	26704	1768	15	Rural	1950-2013
	Jiwani	41756	25.4	61.48	56	18533	313	59	Rural	1950-2013
	Pasni	41759	25.16	63.29	9	33114	420	79	Rural	1950-2013
	Dalbandin	41712	28.53	64.24	848	14623	981	15	Rural	1950-2013

Table 2: Observed trends of $dT_n^{a,s}$, $dT_x^{a,s}$; dT_n^{u-r}, dT_x^{u-r}; dT_n^{t-r} and dT_x^{t-r} ($°C^{-dec}$) for P1 and P2, respectively.

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Period	dT_u , dT_t , dT_r	P1 (1950-1981)		P2 (1982-2013)		Net change from P1 to P2	
		dT_n (°C/decade)	dT_x (°C/decade)	dT_n (°C/decade)	dT_x (°C/decade)	dT_n (°C/decade) (P2 - P1)	dT_x (°C/decade) (P2 - P1)
Annual	dT_u	0.04	-0.03	0.37	0.21	0.33	0.25
	dT_t	0.13	-0.07	0.10	0.16	-0.03	0.23
	dT_r	0.20	0.04	0.03	0.26	-0.18	0.22
	dT_u - dT_r	-0.17	-0.07	0.34	-0.04	0.50	0.03
	dT_t - dT_r	-0.07	-0.11	0.07	-0.10	0.15	0.02
Winter	dT_u	-0.07	-0.11	0.29	-0.02	0.36	0.09
	dT_t	0.04	-0.17	0.21	0.22	0.16	0.39
	dT_r	0.06	-0.06	0.14	0.36	0.08	0.42
	dT_u - dT_r	-0.13	-0.05	0.14	-0.38	0.27	-0.33
	dT_t - dT_r	-0.02	-0.11	0.06	-0.14	0.08	-0.03
Spring	dT_u	0.04	0.10	0.71	0.90	0.67	0.79
	dT_t	0.26	0.05	0.27	0.73	0.02	0.67
	dT_r	0.32	0.26	0.37	0.63	0.05	0.38
	dT_u - dT_r	-0.28	-0.16	0.34	0.26	0.62	0.42
	dT_t - dT_r	-0.06	-0.20	-0.10	0.09	-0.03	0.30
Summer	dT_u	-0.18	-0.23	0.22	-0.09	0.39	0.14
	dT_t	0.07	-0.12	0.08	-0.07	0.01	0.05
	dT_r	0.19	-0.02	-0.02	-0.13	-0.20	-0.11
	dT_u - dT_r	-0.36	-0.21	0.23	0.04	0.60	0.25
	dT_t - dT_r	-0.11	-0.11	0.10	0.05	0.21	0.16
Autumn	dT_u	-0.12	0.02	0.44	0.04	0.56	0.01
	dT_t	0.11	-0.11	0.16	0.09	0.06	0.19
	dT_r	0.08	-0.10	0.14	0.26	0.07	0.36
	dT_u - dT_r	-0.19	0.12	0.30	-0.23	0.49	-0.35
	dT_t - dT_r	0.03	-0.01	0.02	-0.18	-0.01	-0.17

Table 3: Number of stations in four ranges of dT_n^a and dT_x^a for P1 and P2.

dT	**Period**	**dT (°C^{-dec})**				**Total stations**
		< 0	**0 - 0.30**	**0.30 - 0.50**	**> 0.50**	
dT_n^a	P1 (1950-1981)	14	15	5	2	36
	P2 (1982-2013)	11	9	7	9	36
dT_x^a	P1 (1950-1981)	15	20	1	0	36
	P2 (1982-2013)	7	15	6	8	36

Table 4: Percentage of stations showing increasing trends in annual and seasonal T_n and T_x for each type of stations for the period 1950–1981 and 1982–2013.

dT_n and dT_x	Urban	Town	Rural

	1950-1981	1982-2013	1950-1981	1982-2013	1950-1981	1982-2013
dT_n^a	53%	94%	64%	55%	78%	44%
dT_n^{Wi}	56%	88%	45%	64%	56%	67%
dT_n^{Sp}	75%	100%	100%	73%	100%	100%
dT_n^{Su}	19%	88%	36%	64%	78%	56%
dT_n^{Au}	50%	100%	55%	64%	78%	67%
Overall average of % of stations where T_n increased	51%	***94%***	60%	64%	78%	67%
dT_x^a	50%	81%	45%	73%	78%	89%
dT_x^{Wi}	19%	50%	27%	82%	44%	89%
dT_x^{Sp}	63%	100%	64%	100%	100%	89%
dT_x^{Su}	19%	19%	55%	45%	78%	33%
dT_x^{Au}	50%	56%	36%	55%	67%	89%
Overall average of % of stations where T_x increased	40%	61%	45%	71%	73%	78%

Table 5: Summary of the Mann-Kendall test comparing maximum and minimum temperature for urban stations. Significant values (p value<0.05) highlighted in gray.

Stations	**Years of Breaks in T_n trend**	**MK test-T_n (p-value)**	**Years of Breaks in T_x trend**	**MK test-T_x (p-value)**

Urban stations				
Gilgit	none	6.10^{-5}	none	3.10^{-4}
Quetta	none	2.10^{-7}	none	1.10^{-4}
Lahore_ur	none	2.10^{-6}	none	8.10^{-3}
Karachi	none	3.10^{-6}	1968	1.10^{-5}
Hyderabad	none	2.10^{-3}	1967, 1984	0.02
Islamabad	1999	1.10^{-3}	1997	0.01
Multan	none	1.10^{-6}	none	0.45
Sargodha	none	2.10^{-5}	1971, 1999	0.11
Jhelum	none	1.10^{-6}	1996, 2001, 2010	0.81
Kakul	none	1.10^{-5}	1993, 2002	0.27
Sialkot	1975, 1982	0.11	none	1.10^{-4}
Muzaffarabad	1987, 1990	0.48	1997	2.10^{-5}
Peshawar	1998	0.058	1968, 1971	0.07
Bahawalpur	1969,1982	0.37	1969, 1982	0.05
D.I.Khan	1977, 1983	0.17	1974, 2003, 2011	0.37
Faisalabad	1984, 2002	0.12	1969, 2002	0.63
Town stations				
Panjgur	none	2.10^{-7}	none	1.10^{-5}
Badin	none	2.10^{-6}	1971,1977	3.10^{-5}
Jacobabad	none	9.10^{-4}	1969,1975	0.207
Padidan	none	7.10^{-4}	1985, 1994	0.561
Kohat	1964,1987,1994	*0.025*	1985	7.10^{-4}
Risalpur	1969,1982,2012	0.54	1965,1999	*0.039*
Lasbella	1969, 1994, 2000	0.50	1967, 1984	3.10^{-6}
Nawabshah	1994, 2000	0.98	1996, 2002	2.10^{-3}
Chhor	1996, 2003	0.14	none	4.10^{-5}
Skardu	1971, 1987, 2003	0.15	1971,1987,2003	2.10^{-7}
Sibbi	1970, 1988, 2002	0.68	1987,2005	0.74
Rural stations				
Dalbandin	none	1.10^{-7}	none	2.10^{-5}
Astore	none	*0.025*	none	*0.035*
Cherat	1997	5.10^{-3}	none	6.10^{-4}
Bunji	1988	9.10^{-4}	1961, 1988	0.13
Chilas	none	1.10^{-3}	1967, 1999	0.85
Gupis	1969 1993, 2007	0.58	1969,1996, 2007	2.10^{-3}
Jiwani	1979, 2002	0.78	1976	2.10^{-3}
Pasni	1960, 2002	0.13	none	2.10^{-4}
Kalat	1989,2005	0.86	1993,2005	0.59