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Research Article

# A Modeling Approach to Study the Effect of Urban Structure on Minimum and Maximum Temperatures: Application to City Lahore in Pakistan

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## Abstract

During recent decades in Pakistan, dense urban areas generally underwent more warming than rural areas and small towns. Minimum temperatures also generally increase more than maximum temperatures. This study aims to understand why minimum temperatures increase more in urban areas than maximum temperatures. Simulations are performed with an urban climate model for different configurations of urban parameters: city size, land urban fraction, and building heights. The relative effects of these urban parameters on minimum and maximum temperatures are analyzed and used to investigate the evolution of temperatures in the megacity Lahore (Pakistan) from 1980 to 2004. Both minimum and maximum temperatures tend to increase with city size and urban fraction. Higher buildings can lead to higher minimum temperature, but also to lower maximum temperature depending on the season. The simple model reproduces well the difference of evolution in minimum and maximum temperature but overestimates the increase of maximum temperature. Our study indicates that the city size of Lahore appears to be the main factor driving urban warming and its variations.

**Keywords:** Urban temperature; city size; urban fraction; building height; lahore

## Introduction

Climate change is leading to increased temperatures worldwide, changes in weather seasonality and in extreme weather events (e.g., frequency and intensity of heatwaves), and to many impacts on society and ecosystems [1-6]. In addition to climate change, air temperature is often higher in urban areas than in surrounding rural areas due to city geometry (shape and direction of buildings and streets), the heat-retaining properties of artificial materials (such as concrete), and the heat produced from human activities (such as residential heating during winter); [7]. This so-called “urban heat island” (UHI) is increasing with urbanization in many parts of the world [8,9]. Combined with an increase in heatwaves, the UHI represents an important health risk in summer for populations now, and even more in the future [10-13). Urban areas are expected to continue growing in size, population, and building heights [14-16], while several urban planning strategies are proposed to reduce local risks to health and infrastructure, such as to increase the proportion of vegetation and water surfaces in cities [17,18].

The links between urban planning, urbanization, and warming have been highlighted for a long time [19-21]. In 2003 for instance, Kalnay and Cai estimated with about two thousand weather stations in the United States that land-use changes (e.g., urbanization, agriculture) led to about 0.35 °C mean surface warming per century. At local scale, [22] found that UHI intensity is higher near the city center (in Debrecen, Hungary), where the fraction of impervious surface (i.e., urban fraction) is also higher. [23] also highlighted a stronger warming of about 0.57 °C/decade in large cities (>106 inhabitants) than in medium-sized cities (104-106 inhabitants) with 0.37 °C/decade. In their review of the numerical modelling literature about urban heat mitigation, [24] argue that the priority is now to focus on urban thermal comfort. [25] go further and stress the importance of a better quantification of large temperature fluctuations (e.g., extreme weather conditions) in the urban environment. A few studies indicate that the minimum temperature of urban areas is increasing more than the maximum temperature [26-29].

On a global scale, this feature is also noted in rural areas [30,31] and could be explained by different factors, such as changes in atmospheric circulation and an increase in cloud cover [32,33]. On an urban scale, the literature does not clearly explain why minimum temperature increases even more than maximum temperature in the largest cities. The goal of this study is therefore to analyze the factors responsible for this difference in increase between minimum and maximum temperatures. Previous studies related to the topic are based on the analysis of in-situ measurements and/or city-scale simulations. Mesoscale atmospheric models were progressively modified to better consider the impact of urban morphology on urban meteorology [34-39] and have been used for decades to investigate urban processes [40,41]. They are now able to consider physical factors at microscale (e.g., neighborhood morphology) and regional scale (e.g., weather pattern) interacting together [42]. Based on a review of the urban climate literature, several parameters appear essential to examine urban temperatures:

a) City size [43,44].

b) Building heights.

c) Fraction of vegetation or impervious surfaces [45-47].

d) Population density.

The present study investigates the respective effects of city size, urban fraction, and building heights on the evolution of both urban minimum and maximum temperatures by combining urban simulations and observations. The urban simulations are performed with the Finite Volume Model (FVM) developed by [48]. This model was previously used in various studies to simulate the urban climates of different cities and was validated using diverse information sources (meteorological measurements; [49-53]). Here, we first use FVM simulations to describe the urban climate of a Pakistani city and the influence of urban parameters on minimum and maximum temperatures. In a second step, the simulations are used to develop a method to understand the evolution of temperature in the megacity Lahore in Pakistan (second largest city with about 10 million inhabitants). The city is growing and delivering economic incentives to increase the vegetation cover. Pakistan has a rapidly increasing urban population like many other developing countries of the world and has the highest proportion (about 40% today and 60% by 2050) [54] of population living in urban areas in South Asia [55]. The data and methods of the present study are detailed in Section 2, the results are presented in Section 3, and Section 4 concludes with a discussion of the results as well as limitations and perspectives of the study.

## Data and Methods

### Modelling the Impact of Urban Structure on Air Temperatures

The mean air temperature of a city over time depends a lot on the city size, building heights, and the fraction of vegetation. We hypothesize here that these three factors are sufficient to estimate the temperature evolution in a city. The city size is represented by the radius *r* of a circle, representing the whole city. Variable *h* represents the mean building height in the urban area. The urban fraction *u* represents the mean proportion of land that is artificial (i.e., excluding vegetation). The mean temperature *T* computed over the whole city, called city temperature, thereafter, can be written as a function of time *t*, radius *r*, mean height *h*, and urban fraction *u*, such as *T (t, r, h, u)*. And the total derivative of function *T* with time can then be written as follows:

$$\frac{dT}{dt} = \frac{\partial T}{\partial r}.\frac{dr}{dt} + \frac{\partial T}{\partial h}.\frac{dh}{dt} + \frac{\partial T}{\partial u}.\frac{du}{dt} \quad (1)$$

We can then compute the evolution of *T* with time in function of the urban parameters, by knowing the variations of *T* with the three urban parameters and how these urban parameters change with time.

The application of the method to a city can be summarized as:

a) A meteorological urban model is used to estimate the variations of mean city temperature with parameters *r*, *h,* and *u*. This is done by running simulations with different scenarios of theoretical cities to compute

$$\frac{\partial T}{\partial r}, \frac{\partial T}{\partial h}, \frac{\partial T}{\partial u} terms of Equation 1.$$

b) Observations of the evolution of urban parameters for a real city (here Lahore) have been collected for several years and their variations with time

$$i.e., terms \frac{dr}{dt}, \frac{dh}{dt}, \frac{du}{dt} of Equation 1.$$

c) The contributions of each urban parameter changes to the temperature evolution

$(i.e. \frac{\partial T}{\partial r}.\frac{dr}{dt}, \frac{\partial T}{\partial h}.\frac{dh}{dt}, \frac{\partial T}{\partial u}.\frac{du}{dt})$ are computed to be compared.

d) The changes in city temperature due to all urban parameters $(\frac{dT}{dt})$ is estimated and compared to the observed evolution of temperature in the studied city with time.

e) For the purpose of this study, we use Equation 1 to investigate both minimum and maximum temperatures $(T_{min} and T_{max})$.

### Estimating the Effect of Urban Structure on Temperature Evolution with an Urban Climate Model

#### Overview of the Finite Volume Model (FVM)

The Finite Volume Model (FVM) is a non-hydrostatic meteorological model developed by Clappier. This model calculates meteorological variables such as pressure, wind (direction, speed), air temperature, density, and humidity on a terrain-following grid with finite volume discretization. FVM solves the conservation equations of mass, momentum, humidity, energy, and turbulent kinetic energy. The model also includes an urban turbulence module [56] and a building energy model (BEM) [57] that simulate the effects of urban areas on the surrounding atmosphere.

The city is represented in FVM as a combination of several urban classes. Each class is represented by:

a) an urban fraction (i.e., fraction of built surface).

b) building morphology (distribution of height and width, street dimensions, percentage of windows, etc).

c) building physical properties (e.g., materials of floor, walls, and roofs).

d) building radiative properties (e.g., albedo, thermal capacity, conductivity).

FVM was applied in many cities (e.g., Mexico, Athens), and validated with meteorological measurements [58]. In the present study, FVM is used to determine the evolution of a city's mean temperature, when changing the city size, the mean building height, and the mean urban fraction. The next sections describe the simulations that were produced.

**Model Setup for a Typical City in Pakistan**

In order to reduce the complexity of the urban system, we focused on a theoretical city. This city is designed as a circular urban area located in the almost flat plain of central Punjab, at a mean altitude of 175m. This area is far from the mountains located North and West, from the Arabian Sea and from major water reservoirs. We defined two nested grid domains that are centered on the theoretical city:

a) A coarse grid domain with 30 cells and a horizontal resolution of 10km x 10km.

b) A smaller grid domain with also 30 cells but a finer resolution of 4km x 4km.

The vertical resolution ranges from 10m to 18m in the first 55m above the ground and then stretches upward until the tropopause (i.e., 1000m layer at model maximum altitude of 9347m). The model needs as input the:

a) Land topography.

b) Land use (with a detailed description of urban areas).

c) Boundary meteorological conditions (temperature, wind, humidity, atmospheric pressure).

The topography data were extracted from GTOP30. The land use usually used in FVM is the Global Land Cover (GLC) database, but for the purpose of the present study it was modified to describe a round city with specific urban characteristics and homogeneous rural area. The urban characteristics are representative of a typical Pakistani city (i.e., 15m building width and 30m street width). The materials are considered identical for ground, wall, window, roof, and street with few characteristics:

a) Albedo = 0.2

b) Emissivity = 0.9

c) Surface roughness length of the surfaces = 0.01

d) Thermal conductivity = 1.73 $m^2. s^{-1}$

e) Material specific heat = 2.07E+006 $J.m^{-3}. K^{-1}$

f) Initial temperature of the surfaces = 293 K

As forcing boundary conditions of the model, we used realistic (typical) meteorological situations of Pakistan. These meteorological boundary conditions were obtained from the National Center for Environmental Predictions (NCEP) database.

**Simulation of Urban Scenarios with FVM**

To reduce the computing time, the simulations were run only for three days of each month in 2005, starting at 00:00 (GMT) on the 19th day, and ending at 00:00 (GMT) on the 22nd day. Several scenarios were designed to analyze the effect of city factors (size, building height, urban fraction) on temperature:

a) 4 scenarios of city size (radius of 8km, 12km, 16km, 20km).

b) 3 scenarios of building heights (20m with 4 floors, 25m with 5 floors, 30m with 6 floors).

c) 4 scenarios of urban fraction (95%, 90%, 80%, 70%). An urban fraction of 95% corresponds to a densely built city with 95% of land occupied by artificial materials (buildings, roads, and other paved surfaces) and only 5% of land covered by vegetation.

The combination of these scenarios corresponds to 48 urban configurations, which were each investigated by simulations with FVM. The simulated hourly temperatures were first averaged for the whole city to determine a city temperature. To avoid the effect of simulation initialization which can bias the results, the daily minimum and maximum temperatures were computed and averaged only on the two last days of simulation per month. In total 576 values (48*12) were thus produced. The FVM simulations then allow us to determine the variation of city temperature due to a change in:

a) city radius (r)

b) building height (h)

c) urban fraction (u)

These variations can be written as follows:

$$\frac{dT}{\partial p} = \frac{T_{pj} - T_{pi}}{pj - pi} \quad (2)$$

where T (pi) is the city temperature calculated based on the value of an input parameter pi, and T (pj ) is the city temperature for another value of input parameter (pj).

### Temperature Evolution of Lahore Megacity

The method to study the evolution of temperature in Lahore is based on:

a) Analyzing the land use changes in Lahore over different years, to determine the variation of the city radius, urban fraction and building height with time, i.e. $\frac{dpi}{dt}$ terms of Equation 1.

b) Calculating the variation of temperature as a function of the changes in urban structure of Lahore. This calculation uses each term of Equation 1, i.e., the relationships between temperature and urban factors $\frac{\partial T}{\partial pi}.\frac{\partial pi}{dt}$ (city radius, urban fraction and building height) determined with FVM simulations.

c) Analyzing the evolution of temperatures at weather stations in Lahore.

d) Comparing the results from our simulations to the observational data.

The evolution of Lahore's urban parameters from 1980 to 2010 is shown in Table 1. The urban area of Lahore was about 138 $km^2$ in 1980 and increased greatly to about 1,950 $km^2$ in 30 years [59]. The city radius was estimated from the urban area and based on a round city.

**Table 1:** Evolution of urban parameters in Lahore from 1980 to 2010 (based on estimations from census reports and Khaliq-uz-Zaman and Baloch).

| Year | Urban area ($km^2$) | Radius of the city r (km) | Urban fraction u (%) | Building height h (m) |
|---|---|---|---|---|
| 1980 | 138 | 6.63 | - | - |
| 1990 | 629 | 14.15 | 51.4 | 20 |
| 2000 | 961 | 17.49 | 57.1 | 25 |
| 2010 | 1950 | 24.91 | 71.6 | 30 |

$$(with r = \sqrt{\frac{urban area}{\Pi}})$$

The urban fraction is computed from data provided by Almas et al. (2005) and through personal communication with Amjad S. Almas (2010). Due to missing data about building heights, approximate values were calculated based on population density and city size (using estimations from census reports). Overall, the net urban changes are about:

a) 4.4km/decade in city radius

b) 10.1%/decade in urban fraction

c) 5m/decade in building height

The observational temperature data were collected from the Pakistan Meteorological Department on the two weather stations available for Lahore (Figure 1). One is in the Shadman district near the city center, and the other one is at Lahore airport in the periphery of the city. The airport weather station is officially classified as rural but is in the vicinity of built areas and quite influenced by Lahore's urban climate. The daily minimum and maximum temperatures were then homogenized with the HOMER method (version 2.6) and analyzed. Details about the data and homogenization, as well as the evaluation of the temperature trends and discussions about these trends, are provided in Sajjad. The temperature trends of the period 1980-2004 are also reported in section 3.4. Though the urban station is probably not representative of the mean city temperature, the time evolution of the temperature observed on this station will be compared with the one estimated from Equation 1 to evaluate the order of magnitude of our estimations. This representativity issue will be a source of uncertainty in the comparison.

## Results

### Effect of City Size on UHI and Wind

For conciseness and since many simulations were done, a single example of results with FVM is given in Figure 2. This figure illustrates the surface temperatures and winds simulated by the model on the day 20.04.2005 (morning and afternoon) for a city radius of 8 km and 20 km, building height of 20m and urban fraction of 80%. The temperature appears higher over urban areas than rural areas), and this UHI is stronger when the city size increases. The UHI also leads to the convergence of wind over the city during the morning and afternoon. One can note that the temperatures are not homogeneous over the city. They are often higher downwind in the city.

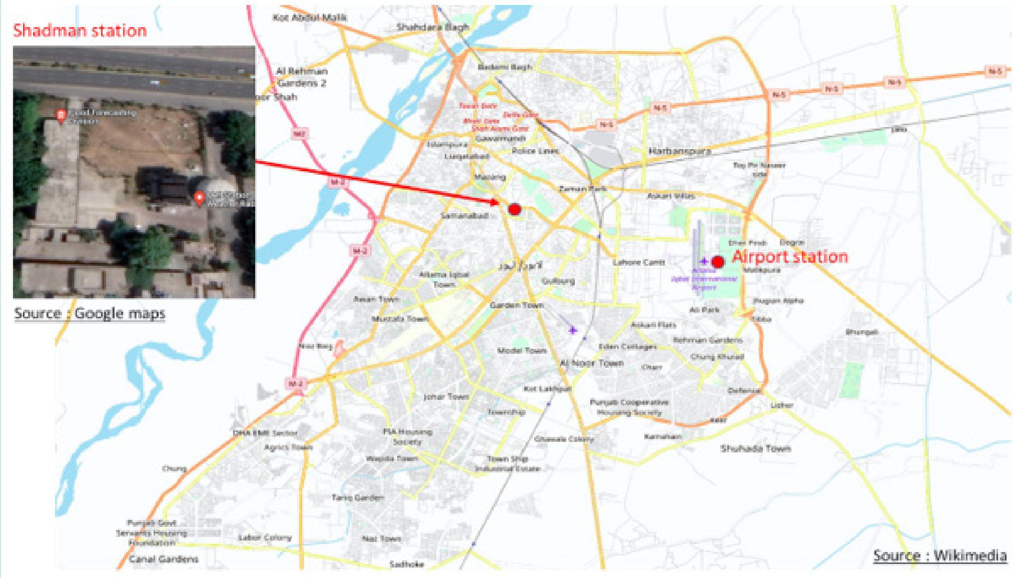


**Figure 1:** Location of weather stations in the Lahore area.

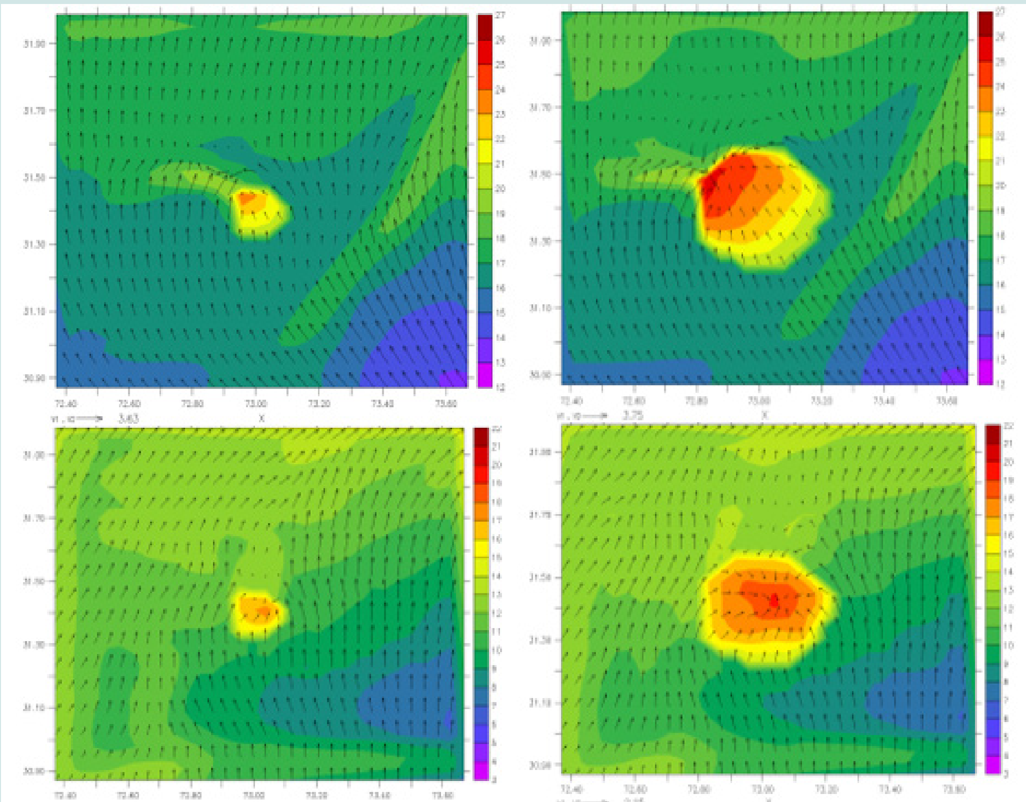

**Figure 2:** Surface temperatures and winds simulated by FVM 20.04.2005 at 09:00 GMT (top) and 17:00 GMT (bottom) for a city with a radius of 8 km (left) and 20 km (right), a building height of 20m and an urban fraction of 80%. The spatial resolution is 4km by 4km, and the wind speed is in m.s-1 (the arrow drawn on the bottom left corner of each map gives the scale).

## Effect of Urban Structure on Annual Temperatures

The variations of annual temperatures (minimum, mean, maximum) with different urban parameters are summarized in Table 2 for the 576 simulations (48 scenarios and 12 months). The results indicate that increasing the city size or the urban fraction always leads to higher minimal and maximal temperatures. However, an increase in building height generally leads to an increase in minimum temperature (about 95% of cases) but also to a decrease in maximum temperature (about 61% of cases). To further investigate the mechanisms for these temperature variations, the differences in variations of minimum and maximum temperatures (averaged on all months and urban parameter variations) are shown in Table 3. When building height increases, minimum temperature increases more than maximum temperature (about 98% of cases). An increase in urban fraction can lead to a slightly higher increase in maximum temperatures than in minimum temperatures (about 93% of cases). The effect of city size is less clear, as either minimum or maximum temperature tends to increase more (about half of cases).

**Table 2:** Annual values (minimum, mean, maximum) of the variation in minimum and maximum temperature with city radius, urban fraction, and building height. The last column shows the percentage of simulations with a positive change in temperature for an increase in urban parameter.

| Annual values of all the scenarios | Minimum value | Mean value | Maximum value | % of positive values out of all the simulations |
|---|---|---|---|---|
| $d\,T_{min}/dr$ (in K/km) | 0.10 | 0.13 | 0.20 | 100% |
| $d\,T_{max}/dr$ (in K/km) | 0.07 | 0.11 | 0.18 | 100% |
| $d\,T_{min}/du$ (in K) | 0.01 | 0.02 | 0.03 | 100% |
| $d\,T_{max}/du$ (in K) | 0.02 | 0.03 | 0.05 | 100% |
| $d\,T_{min}/dh$ (in K/m) | 0.00 | 0.04 | 0.08 | 95% |
| $d\,T_{max}/dh$ (in K/m) | -0.12 | -0.03 | 0.02 | 39% |

**Table 3:** Annual mean differences of variations in minimum and maximum temperatures as a function of urban parameters (city size, urban fraction, building height).

| Annual values of all the scenarios | Annual average | % of positive values out of all the simulations |
|---|---|---|
| $d(T_{min} - T_{max})/dr$ (in K/km) | 0.02 | 59% |
| $d(T_{min} - T_{max})/du$ (in K) | -0.01 | 7% |
| $d(T_{min} - T_{max})/dh$ (in K/m) | 0.07 | 98% |

## Effect of City Radius on Seasonal and Monthly Temperatures

To better understand the effect of city size on temperature, an analysis per season and month is presented in Table 4. This table shows the differences between the variation in minimum and maximum temperature, averaged over months and seasons, in function of the city radius. The temperature differences appear to vary largely depending on the season and month. An increase of city radius has two main effects: it tends to increase minimum temperature more than maximum temperature in colder months (especially in winter), but it also tends to increase maximum temperature more than minimum temperature in warmer months (especially in May and July). It can also be noted that despite monthly variations, the effect of city radius in spring and autumn is almost the same on minimum and maximum temperatures since the seasonal average difference is nearly zero and about half of simulations show either a higher increase in $T_{min}$ or in $T_{max}$. These results suggest an important impact of solar energy and its interaction with the city.

**Table 4:** Monthly and seasonally averaged differences (K/km) between changes in minimum and maximum temperature with variations in city radius.

| $d(T_{min} - T_{max})/dr$ | | | | | |
|---|---|---|---|---|---|
| **Season** | **Seasonal average (K/km)** | **Seasonal % of positive values** | **Month** | **Monthly average (K/km)** | **Monthly % of positive values** |
| Winter | 0.09 | 98% | December | 0.088 | 100% |
| | | | January | 0.048 | 94% |
| | | | February | 0.131 | 100% |
| Spring | 0.01 | 58% | March | 0.016 | 78% |
| | | | April | 0.062 | 97% |
| | | | May | -0.041 | 0% |

| | | | | | |
|---|---|---|---|---|---|
| Summer | -0.02 | 30% | June | -0.001 | 44% |
| | | | July | -0.068 | 0% |
| | | | August | -0.002 | 44% |
| Autumn | 0.01 | 51% | September | -0.005 | 39% |
| | | | October | -0.014 | 31% |
| | | | November | 0.055 | 83% |

During winter, less solar energy is absorbed by the city and contributes to heating the city than in summer. Nevertheless, the UHI is more important in winter than in summer. When city size increases, the city temperature is mainly influenced by two processes: the increase in heat absorbed by the city during sunny hours, and the decrease of wind inside the city (more important during less sunny hours, when the air convection is less important). The two processes have opposite effects on air mixing in the city: the increase in absorbed heat leads to an increase of vertical air mixing, while the decrease of wind leads to a reduction of vertical air mixing. During winter, night air mixing is weak which favors an increase of city minimum temperature, while during the day air convection is stronger which brings colder air from surrounding areas to the city and disfavors an increase in city maximum temperature. During summer, the increase in heat absorbed by the city leads to strong air mixing but the air brought from surrounding areas has closer temperature (UHI less important in summer than in winter), favoring an increase of maximum temperature rather than minimum temperature.

## Evolution of Lahore Temperatures: Comparison Between Simulations and Observations

To study the evolution of temperatures in Lahore, the evolutions of urban parameters (city radius, urban fraction, building height) were combined (using Equation 1) with the effects of urban parameters on temperature (determined with FVM simulations). The changes in minimum and maximum temperatures due to each urban parameter are shown in Table 5. According to our method, the contribution of city radius to the increase of minimum and maximum temperatures is more important than the contribution of urban fraction and building height. Table 6 presents a comparison of the temperature changes observed at two weather stations and simulated in Lahore during 1980 to 2004. Though both weather stations give local information compared to the model (i.e., specific local factors other than the parameters considered in this study may also influence the observations without being represented in FVM), and the model indicates only changes due to urban structure, the comparison is done to evaluate the order of magnitude of temperature changes.

**Table 5:** Changes in minimum and maximum temperatures in the Lahore area during 1980 to 2004 estimated due to respective changes in city radius (r), urban fraction (u) and building height (h).

| 1980-2004 | $T_{min}$ (K) | $T_{max}$ (K) | $T_{min}$ (%) | $T_{max}$ (%) |
|---|---|---|---|---|
| dT/dr*dr/dt | 1.66 | 1.38 | 60.00% | 71.00% |
| dT/du*du/dt | 0.6 | 0.98 | 21.70% | 50.30% |
| dT/dh*dh/dt | 0.51 | -0.41 | 18.30% | -21.30% |
| ΔT | 2.76 | 1.94 | 100% | 100% |

**Table 6:** Changes in minimum and maximum temperatures observed between 1980 and 2004 at Lahore rural and urban stations and estimated in Lahore city.

| Period: 1980-2004 | | | |
|---|---|---|---|
| **Location** | **$\Delta T_{min}$ (K)** | **$\Delta T_{max}$ (K)** | **$\Delta (T_{min}-T_{max})$ (K)** |
| Lahore airport station (observed) | 1.2 | 0.47 | 0.73 |
| Lahore Shadman station (observed) | 2.65 | -0.39 | 3.04 |
| Simulated Lahore city (estimated with the model) | 2.76 | 1.94 | 0.82 |

As expected, minimum temperatures increased more than maximum temperatures. The increase of minimum temperatures was higher near the city center (Shadman station), than in the periphery of the city (airport station). The simulations agree with observations on a higher increase of minimum temperatures than maximum temperature in Lahore, even if the model tends to overestimate the temperature increases. A decrease of maximum temperature is only observed at the Shadman station, and not Lahore airport or other cities around (Table 7). Since all cities in the province of Penjab experienced particularly low temperatures in 1997

[60], we calculated the temperature trends with and without 1997. Excluding 1997 from the trend calculation, the change of maximum temperature at Lahore (Shadman station) is largely reduced (-56%), although still negative. The discrepancy between observed and simulated change in maximum temperature in Lahore could be driven by different factors:

**Table 7:** Comparison of temperature changes between cities in the Punjab region.

| Location | City size ($km^2$) | $\Delta T_{min}$ (K) | $\Delta T_{max}$ (K) | $\Delta (T_{min} - T_{max})$ (K) |
|---|---|---|---|---|
| Lahore (Shadman) | 659 | 2.65 | -0.39 | 3.04 |
| Faisalabad | 214 | 1.54 | 0.91 | 0.63 |
| Multan | 199 | 1.01 | 0.11 | 0.9 |
| Sialkot | 92 | 0.56 | 0.56 | 0.18 |
| Sargodha | 55 | 0.72 | 0.27 | 0.45 |
| **Results without year 1997** | | | | |
| Lahore (Shadman) | - | 2.71 | -0.17 | 2.88 |
| Faisalabad | - | 1.62 | 1.11 | 0.51 |
| Multan | - | 1.08 | 0.29 | 0.79 |
| Sialkot | - | 1.03 | 1 | 0.03 |
| Sargodha | - | 0.74 | 0.49 | 0.25 |

a) Urban factors (e.g., air circulation; an underestimation the impact of higher building heights) and regional factors (weather patterns) would probably also affect the temperatures recorded at the airport station, which leads to the possibility of very local effects at the Shadman station.

b) Specific local practices (such as measurement methods or land watering) would probably also affect minimum temperature.

c) Land use changes but a vegetation increase around the station is unlikely given the surrounding built area.

d) Local air pollution may affect the energy surface balance (with less surface solar radiation during the day and more infrared energy absorption during the night). These processes would tend to increase the minimum temperature and decrease the maximum temperature. Rasheed [61] studied air pollution in several Pakistani cities and concluded that the average PM2.5 mass concentration is significantly higher in Lahore than in the other cities. The Shadman station is moreover located near a highway, of which PM traffic emissions may influence the measurements [62-69].

To conclude, the links between local air pollution and temperatures need further investigation. Rasheed found an association between higher air pollution and lower temperature, but this association is certainly due to diurnal variations of air mixing (i.e., high temperatures usually lead to strong air mixing and lower PM concentrations). It would be interesting to have data from a nearby rural station to better understand the contribution of climate change to the increase of the minimum and maximum temperatures. This contribution cannot be simulated in this study.

## Conclusion

The study aimed to understand how the urban structure (city size, urban fraction, building height) can influence differently the evolution of minimum and maximum temperatures. Using a simple equation, the evolution of temperature in a city over time was estimated as a function of different urban parameters. The FVM meteorological model was used to determine the effect of the urban parameters on minimum and maximum temperatures (annually, seasonally, and monthly) with simulations of a theoretical round city. These estimated relationships between urban parameters and temperatures were then used to determine the contribution of each urban parameter to the evolution of temperature for a real case study: the city Lahore in Pakistan. Considering different urban structures, the FVM simulations showed that urban temperatures increase with the city size and with the urban fraction. The simulations also showed that an increase in building height may lead to higher minimum temperature but also to lower maximum temperature. With higher buildings, the city may become less efficient at absorbing direct solar radiation due to increased shadow effects during the day (leading to a lower maximum of $T_{max}$) and may become more efficient at keeping heat during the night (leading to a higher minimum of $T_{min}$).

The analysis also showed that maximum temperature increases more than minimum temperature when urban fraction increases (i.e., when the proportion of vegetation decreases). We also found that the influence of city size depends largely on the season: minimum temperature increases more than maximum temperature during winter, while maximum temperature increases more than minimum temperature during summer. An increase in city size may therefore lead to more efficiency at keeping heat in winter, and less efficiency at losing heat in summer. These results are consistent with several other studies showing that minimum temperatures are increasing more than maximum temperatures, for instance in the largest Pakistani cities in winter. Our results suggest that this could be due to an increase of urban size and building height. Sajjad also showed that over small towns, maximum temperature increases more than minimum temperature. Our results suggest that this could be explained by an increase in urban fraction (i.e. replacement of natural land cover by artificial materials). The results from the FVM simulations were then compared to observations of the city Lahore, to estimate the contribution of urban parameter variations to the evolution of temperatures.

The effect of city size appears as the dominant factor causing the local increase of minimum and maximum temperatures, and minimum temperatures increased more than maximum temperatures. The comparison with observations also showed that the simulations could skillfully reproduce the higher increase in minimum temperature than in maximum temperature. The model failed however to reproduce the evolution of maximum temperature (no warming observed vs. large warming simulated). This discrepancy could be due to a few factors: the model is a simplified approximation of the real city (e.g., round representation; uncertain evolution of building heights) and physical processes (e.g., climate change is not included) but the temperature observations are also uncertain (i.e., potentially influenced by local effects, and not representative of city temperature). Further investigations need to be performed on other city locations with urban and nearby rural temperature measurements. Urban measurement networks are still relatively recent and under development in many cities of the world.

A few improvements with our approach could be expected in further investigations:

a) Include additional urban parameters (e.g., population density, non-residential buildings) and other factors (e.g., regional climate change) in the analysis.

b) Do a comparative study on different cities to better address the physical mechanisms driving the effects of urban parameters on temperatures (minimum, mean, maximum).

c) Investigate the local impact of air pollution on long-term temperatures.

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## Data Availability

The NCEP data can be accessed at www.nws.noaa.gov. The GTOP30 data can be accessed at http://www1.gsi.go.jp/geowww/globalmap-gsi/gtopo30/gtopo30.html. The GLC data can be accessed at http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php.

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