Study of Urban Heat Island of Karachi by Using Finite Volume Mesoscale Model

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Abstract: Karachi is the largest and most populous metropolitan city of Pakistan and the main seaport and financial centre of the country. Rapid urbanization during last 40 to 50 years caused to accelerate its population to 23.7 million. The objective of this work was to study the impact of urbanization on development of urban heat island (UHI) of Karachi city. The study was conducted by using Finite Volume Mesoscale Model (FVM) in which topography from GTOPO30, land-use from GLC 2000 and Meteorological data from NCEP were used as an input to run the simulation. The simulations were run for three days starting at 00:00 (GMT) on 19th day of April and ending at 00:00 (GMT) on 22nd day of April over selected domain with resolution of 3x3 km of 30 cells. The results showed that there is significance urban heat island presence in Karachi city where the urban area has 5.6°C to 13.5°C higher temperature than its surrounding non-urban areas depending upon the time of a day.

Keywords: Urbanization, Finite Volume Mesoscale Model, Karachi, urban heat island.

1. INTRODUCTION

United Nations population estimates and projections show that in mid-2013, the world population was 7.2 billion. Further projections show that within the next twelve years, global population will reach to 8.1 billion in 2025, and to further increase to 9.6 billion in 2050 and 10.9 billion by 2100 [1]. Scientists have projected that global average temperature will increase about 1.4°C to 5.8°C by the end of 21st century [2]. However, the sizeable population of urban world is facing severe environmental threats. The lives and livelihoods of hundreds of millions of people living in urban areas will be affected by what is done (or not done) in cities with regard to climate change over the next 5–10 years [3].

Urban heat island (UHI) is one of the most well-known phenomena that narrates that the air temperature in urban areas is normally measured higher than surrounding non-urban areas. The UHI intensity is not homogeneous with different urban sizes, characteristics of urban surface, heat released from anthropogenic activities, topography of the area and local meteorological conditions [4, 5]. The main contributors to UHI are difference in albedo of urban and rural areas, moisture, surface roughness and heat capacity of the material [6]. In addition waste heat from urban activities has also been identified as a key factor to cause UHI. Urban heat island also occurs through alteration of natural surface (vegetation cover) into built surfaces (buildings, roads etc.). The built material of urban surfaces traps incoming solar radiation during the day and then re-radiates it at night [7, 8], thus cause heat island in and over urban areas. UHI may be up to 10 – 15°C under optimum conditions [7]. The extra increase of temperature of urban areas due to the UHI factor causes to boost the demand of energy demand for cooling purpose. But, electricity demand in cities increases by 2–4% for each 1 °C increase in temperature. In this way, about 5–10% of the urban areas electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.0 °C in urban temperatures [9].

Pakistan is home of 180 million of population. Currently, about 40% of its population is living in urban areas. According to an estimate of United Nations, Department of Economic and Social Affairs, about 60% of total population of the country will be living in urban areas up to 2050 [10]. Different studies highlight that during last 3 decades, Karachi has faced a mass urbanization [11, 12]. According to World Population Review, in 2014, Karachi has an estimated population of more than 23.7 million (13% of total population of Pakistan), which makes it the third-largest city in the

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world by population with a population density of over 24,000 people per km^2. In 1955, Karachi city was spread over 104.26 km^2 that reached to 785.45 km^2 in 2006 with an increase of 653% in 5 decades [13]. In this context, the objective of this work is to study the impact of urbanization on development of urban heat island phenomenon during different hours of a day.

2. MATERIALS AND METHODS

2.1. Finite Volume Mesoscale (FVM) Model

For this study, the meteorological model Finite Volume Mesoscale (FVM) was used [14]. This model is based on the method of finite volume in which the atmosphere is divided into boxes of fixed volumes in three dimensions (x, y, z). The equations of conservation laws of mass, momentum and energy are resolved within each of these volumes.

2.2. Model Setup for Simulations

Nesting procedure was used to interpolate the meteorological data to study UHI over the case study area. Initially the larger domain with grid cell dimensions over x and y axis was selected to 30 cells with a resolution of 7x7 km. Then the study area's domain was fixed within the larger domain in which 30 cells of resolution of 3x3 km are selected (Figure **1**). For adjustment and interpolation of meteorological data, the smaller domain (3x3) was nested with the larger domain (7x7).

The vertical resolution ranges from 10 m to 18 m in the first 55 m above the ground and then it keeps on stretching as the distance from the ground increase to its maximum limit of 1000 m at the model top (9347 m). The top of the vertical axis is the tropopause, which means that in this study only troposphere is considered for forcing and for the simulations. The time for all the simulations run in this study was homogeneously fixed. All the simulations for selected time were run for three days starting at 00:00 (GMT) on 19th day of April and ending at 00:00 (GMT) on 22nd day of April 2005. The selection of the year 2005 to study UHI of Karachi was due to the availability of data derived from other sources to use as an input in the model.

2.3. Model input and Data Acquisition

The model was designed on three major features: topography, land-use and meteorological conditions. The data about topographic information was derived from GTOPO30. It is a global Digital Elevation Model (DEM) that has a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer). The land-use data as an input in FVM was taken from Global Land Cover 2000. The meteorological data (wind, temperature, pressure and humidity) for the forcing of boundaries were derived from National Center for Environmental Predictions (NCEP) data base.

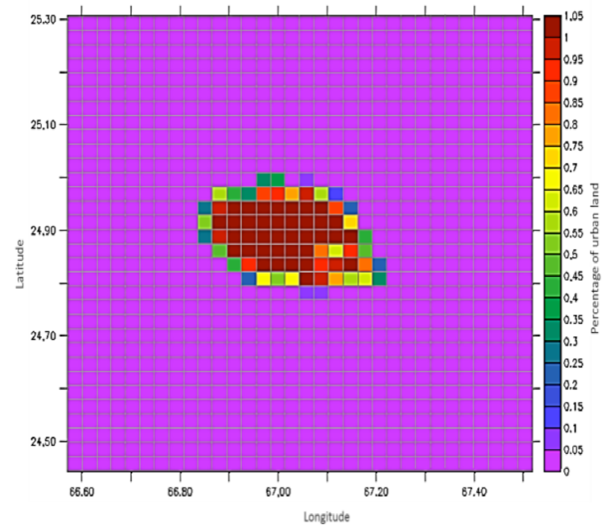

Figure 1: Representation of domain of 30 cells with a resolution of 3x3 km. The shading colors show the percentage of urban class in selected domain.

3. RESULTS AND DISCUSSION

The results highlighted that the FVM model is a suitable method to study the interaction between atmosphere and urban areas. It was observed that the presence of urban areas has greater effect on local

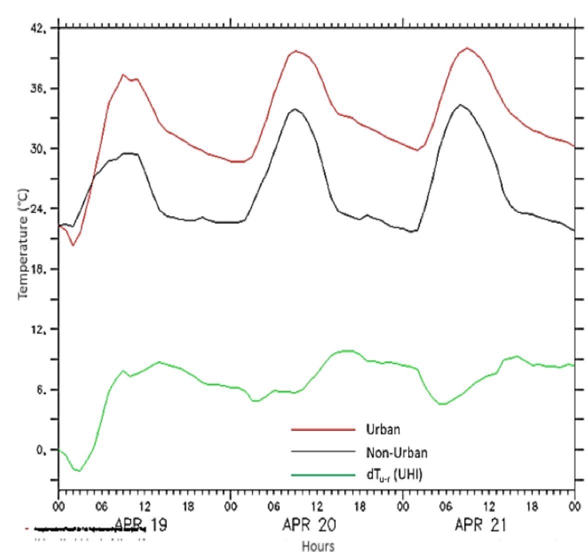

Figure 2: Temperature at urban (solid red line) and rural sites (solid black lines) and the difference between urban and rural areas (solid green line) temperature (dT_{u-r}).

temperature trends and on acceleration of temperature at local scale as compare to non-urban or rural areas. Figure **2** shows the temperature at urban areas (solid red line), rural areas (solid black line) and the difference between urban and non-urban areas temperature (dT_{u-r}), solid green line. The temperature of urban site is calculated by taking the average of temperature of all the cells having urban characteristics (land-use) in selected domain. While for rural temperature, it is calculated by taking the average of temperature of all cells with rural characteristics.

The results show a great difference temperature of urban and rural areas where it showed the higher temperature over urban sites as compared to non-urban sites. Mostly this difference is seen during night times. As Karachi is a big city and it is located on Arabian Sea coast, the presence of UHI during day time is also visible however the intensity of UHI is greatly higher during night times as is the case of many other cities of the world [15, 16, 17].

Figure **3** highlighted that during 24 hours of a day there is great variability in intensity of urban heat island. The simulations run for three days from 19 to 21 April 2005, show that the intensity of UHI is maximum after sun set and during the day is minimum. In Figure **3**, it can be seen that on 20 April 2005, according to

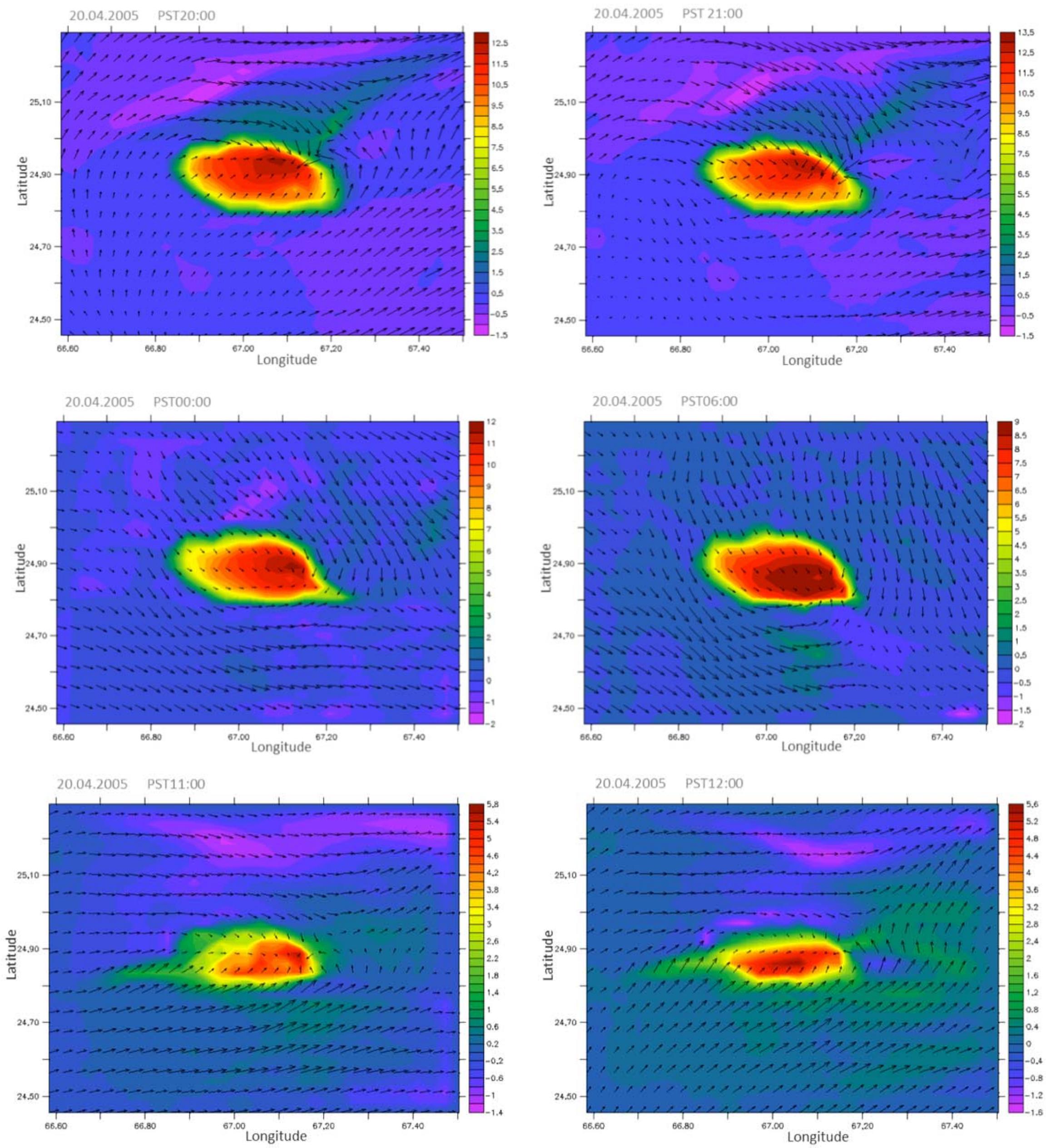

Figure 3: Urban Heat Island of Karachi during different hours of a day (PST 00:00, 06:00, 11:00, 12:00, 20:00 and 21:00).

Pakistan Standard Times, UHI at 06:00 is 9°C, at 11:00 it is 5.8°C and at 12:00 it is observed 5.6°C. UHI during night is measured higher as compare to day times. According to Pakistan Standard Times, UHI at 20:00, 21:00 and 00:00, is observed 13°C, 13.5°C and 12°C, respectively.

The results clearly indicated that during day times when there is solar radiation received on urban and rural areas, there is low intensity of UHI. During the day times, the urban material/surfaces absorbed the heat from solar radiation. This heat traps inside urban canyon and remain in urban canyon. At night times, when there is no sun, the absorbed heat by the surface material starts to release into urban atmosphere, thus causes to warm the urban surface more than its surrounding rural areas and strengthen the phenomenon of urban heat island.

4. CONCLUSION

The major focus of this work was to study the urban heat island of Karachi, a mega city of Pakistan by using a non-hydrostatic mesoscale mode (Finite Volume Model – FVM). The objective of the study was how the urban area effects on development of UHI. The application of Finite Volume Model (FVM) was applied first time on any city of Pakistan. Topography derived from GTOPO30, land-use derived from GLC 2000 and Meteorological data obtained from NCEP was used as an input of the model to run the simulation. The simulations were run for three days starting at 00:00 (GMT) on 19th day of each month and ending at 00:00 (GMT) on 22nd day April 2005 over selected domain with resolution of 3x3 km for 30 cells. The significant presence of urban heat island in different hours was observed that ranged from 5 – 13 °C. The highest UHI was observed during night times and comparatively less during day times.

Although in this study, the causes of higher UHI in Karachi are not identified, there may be several contributing factors in development of UHI. Karachi is an industrial city that consumes plenty of energy resources. Some studies suggest that with less vegetation cover and more artificial materials (concrete, road bitumen, buildings), the urban areas modify the energy absorbed by the soil and emitted to the atmosphere. Moreover, in urban areas, a lot of energy is consumed to support the anthropogenic activities (transport, industry, heating, cooling etc.) which causes the release of extra heat from anthropogenic sources. Consequently, the temperature inside urban areas starts to rise than non-urban areas in their surrounding areas, the well-known phenomenon of urban heat island (UHI). The higher presence of UHI in Karachi may be due to these factors but there is a need study it further. Although these results are extracted for simulation method which will further be compare with observational data of selected stations in Lahore city.

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