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Study of intra-city urban heat island intensity and its influence on atmospheric chemistry and energy consumption in Delhi

Neha Yadav[a,b], Chhemendra Sharma[a,b,*], S.K. Peshin[c], Renu Masiwal[a,b]

[a] Academy of Scientific and Innovative Research, India
[b] CSIR- National Physical Laboratory, Dr. K.S. Krishnan Road, New Delhi 110012, India
[c] India Meteorological Department, Lodi Road, New Delhi 110001, India

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ABSTRACT

Urban heat island intensity (UHII) has been determined as difference in air temperatures between two locations of Delhi namely Safdarjung (SAFD) and National Physical Laboratory (NPL) regions which represent urban and sub-urban areas respectively. High UHI has been obtained in morning time as compared to day and night times, with the highest magnitude ranging from 2.8 to 3° C in spring (MAM), autumn (SON) and winter (DJF) seasons in morning hours (0700–0900 h). Monsoon season (JJA) shows less UHII values compared to other seasons. Wind speed reduced the UHII. Larger impervious area (i.e. 67.2% in SAFD as compared to 33.4% in NPL), lesser vegetated area (i.e. 32.8% in SAFD as compared to 66.6% in NPL) and low Normalized Difference Vegetation Index (NDVI) value (0.15 in SAFD as compared to 0.24 in NPL) in SAFD area supports the existence of UHI there. Ambient O_3 concentrations show maximum values during April and May for both regions and remain insignificantly influenced by UHI. Intra city temperature difference of 0.2–3 °C is capable of raising electricity demand by 37.87–1856 GWh over the base electricity requirement of the city with corresponding increase in CO_2 emissions by 0.031–1.52 million ton.

1. Introduction

Various anthropogenic and industrial activities in urban habitations make a visible climate impact in the form of increase of temperature of the air close to the ground as compared to its surrounding rural areas. This phenomenon is called the urban heat island (UHI) effect (Oke, 1982; Kim & Baik, 2005; Emmanuel & Kruger, 2012). The main cause of UHI is replacement of natural land with artificial built surfaces which are made up of brick, concrete, asphalt, stone, and other similar surfaces typical to urban areas having a significantly high heat capacity and thermal admittance that can capture and store higher quantities of heat. This subsequently increases near surface temperatures of surrounding urban environment (Akbari, Pomerantz, & Taha, 2001). This increased energy is then slowly released to the atmosphere during the night as long-wave radiation, making cooling a slow process and thus elevated nighttime (typically minimum daily) temperatures becomes a key characteristic of the UHI effect (Dimoudi & Nikolopoulou, 2003). Anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources significantly contribute to intensify the UHI effect (Ichinose, Shimodozono, & Hanaki, 1999; Taha, 1997; Sailor, 2011). With the increasing trend of urbanization, urban population gets affected in terms of energy consumption and health especially in the summer. Influence of ambient air temperature fluctuations on energy consumption is directly related to degree days and has been examined by researchers (Gupta, 2012; Moustris et al., 2015). Heating degree days (HDDs) are calculated by subtracting the outdoor temperature from the base temperature, taking into account only positive values, likewise cooling degree days (CDDs) are calculated from temperatures above the base temperature. In case of HDD, the base temperature is considered as the temperature above which there is no need for a building to be heated and in CDD, it is the temperature below which no cooling is needed. Due to higher temperatures heat islands often accelerate the formation of harmful smog as the ozone precursors such as oxides of nitrogen (NOx) and volatile organic compounds (VOCs) combine photochemically to produce ground level ozone (Lo & Quattrochi, 2003; Cardelino & Chameides, 2000). The strong positive relation between ground level ozone or "bad" ozone and high temperature is well established (Jacob & Winner, 2009). High temperatures enable the basic chemical reactions that create ground-level ozone which in turn increases the potential for human exposure to harmful ozone concentrations (Leibensperger, Mickley, & Jacob, 2008).

Aside from the effect on temperature, UHIs can produce secondary

* Corresponding author at: CSIR - National Physical Laboratory, India.
E-mail address: csharma@nplindia.org (C. Sharma).

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effects on local meteorology, including the altering of local wind patterns, the humidity, and the rates of precipitation. The strongest UHIs are observed when skies are clear and winds are calm. As wind speeds increase, turbulent mixing reduces temperature differences in the near surface air. UHI is significantly influenced by the land use/land cover (LULC) pattern like the area covered under vegetation, built up, roads etc. (Hawkins et al., 2004; Jiang & Tian, 2010; Noro & Lazzarin, 2015; Noro, Lazzarin, & Busato, 2015; Busato, Lazzarin, & Noro, 2014). Normalized Difference Vegetation Index (NDVI) is one of the important indexes that give the quantitative estimation of vegetation cover present in any area by taking advantage of the unique spectral characteristics of green vegetation. Mallick, Kant, and Bharath (2008) have used Landsat 7 ETM^+ data and got strongest correlation between land surface temperature and NDVI values over dense vegetation (−0.752) followed by sparse vegetation (−0.709), agricultural cropland (−0.687) and commercial/industrial land use (−0.626) for Delhi. Mohan, Kandya, and Battiprolu (2011) have found the warming trends in temperatures in the National Capital Region (NCR), Delhi by using temperature data of four meteorological stations namely Safdarjung, Palam, Gurgaon and Rohtak.

The present study focuses on intra-city urban heat island investigation using the two sites in Delhi megacity namely, the areas around Safdarjung (SAFD) and National Physical Laboratory (NPL) based on the meteorological data of four years (January 2010–December 2013) and land use data. Urban heat island intensity (UHII) has been calculated as the temperature difference between these two areas. Temporal variation of urban heat island has been presented by computing the diurnal pattern of UHII for SAFD area in winter, spring, monsoon and autumn seasons. This study also investigates the influence of environmental variables such as wind speed and relative humidity on UHI. The concentrations of ambient ozone and precursor gases for both the areas have been presented. The study also attempts to find out the possibility of any influence of UHI on surface ozone concentration in Delhi. Ambient O_3 in Delhi has been reported by a number of authors (Chakrabarty & Peshin, 2016; Sharma, Sharma, Rohtash, & Mandal, 2016) earlier in which UHI effect was not considered. Land use/land cover map and NDVI images of both the areas have been prepared to understand the influence of respective land use pattern on UHI. The effect of UHI on electricity consumption has also been estimated by using the correlation between temperature rise and electricity consumption for the city and the corresponding increase in CO_2 emissions has also been reported.

2. Study area

Delhi, the capital city of India, is situated between latitude 28° 23′ 17″–28° 53′ 00″ North and longitude 76° 50′ 24″–77° 20′ 37″ East. It covers an area of 1483 km^2 and as per 2011 census classification, out of Delhi's total area, 1113.65 km^2 is classified as urban area and 369.35 km^2 as rural area. Two sites in Delhi, namely area around National Physical Laboratory (NPL), New Delhi (situated at latitude 28° 38′ 15″ North and longitude 77° 10′ 11″ East) and area around Safdarjung (SAFD), New Delhi (situated at latitude 28° 35′ 4″ North and longitude 77° 12′ 20″ East), have been selected for the present study (Fig. 1a).

The NPL area has large agricultural fields of the Indian Agriculture Research Institute in its vicinity and represents sub-urban site while the SAFD area is comparatively more thickly populated and represents an urban site. The availability of meteorological stations (Fig. 1d) and air quality monitoring stations (AQMS 1 & 2) at both these areas ensured the availability of required meteorological data and air quality data for the present study. For comparing LULC features in both the sites, an area of 3 km^2 around the meteorological stations located in NPL area (Fig. 1b) and SAFD area (Fig. 1c) have been investigated.

3. Data collection and analysis

3.1. Meteorological data

Hourly data of ambient air temperature, relative humidity and three hourly data of wind speed and wind direction for four year period (January 2010–December 2013) was obtained from Indian Meteorological Department's (IMD) meteorological station situated in Safdarjung (SAFD) area. Meteorological data for similar time period recorded by meteorological tower situated in National Physical Laboratory (NPL) campus has also been used. In order to study the characteristics of the hourly daily temperature values for the period 2010–2013 obtained from both the meteorological stations located at NPL and SAFD areas, a statistical analysis has been performed to test the difference of means. The Student's *t*-test compares the means of two data sets which are related to each other and find out if the two sets of data are significantly different from each other. The test proceeds with a null hypothesis that there is no significant difference between the two means. The calculated value of t has to be compared with the table value at specified level of significance with n–1 ° of freedom. If the computed value is higher than the table value for a given significant level the null hypothesis is rejected and therefore it can be concluded that there is a significant difference between the two means.

3.2. Computation of Urban Heat Island Intensity (UHII)

UHII has been computed as the air temperature difference between SAFD area and NPL area. Diurnal variation of mean hourly UHII have been computed for winter (DJF), spring (MAM), monsoon (JJA) and autumn (SON) by averaging hourly UHII for the years 2010 through 2013. Frequency of UHII has been observed for the night time (2000–0600 h) and daytime (1000–1800 h). Association of UHI with meteorological parameters such as wind speed and relative humidity has been studied by carrying out regression analysis of UHII with wind speed of the SAFD area and the relative humidity difference (ΔRH). The mean hourly relative humidity difference has been computed by subtracting the mean hourly RH of NPL area from that of the SAFD area.

3.3. Degree days

Heating degree days (HDD) and cooling degree days (CDD) of winter (DJF) and spring (MAM) months respectively for the period 2010–2013 by using hourly temperature values for both NPL and SAFD have been calculated by using formula as suggested by Papakostas, Michopoulos, Marvomatis, and Kyriakis (2013).

$$HDD = \frac{1}{24}\sum_{i=1}^{HR}(t_{base} - t_h)^+ \tag{1}$$

$$CDD = \frac{1}{24}\sum_{i=1}^{HR}(t_h - t_{base})^+ \tag{2}$$

Where HR is the number of hours of the month and t_{base} is the base temperature (15 °C for heating and 24 °C for cooling used for this study). + Sign indicates that only positive values have been considered.

3.4. Electricity demand and GHG emissions

As shown in Fig. 2, line of best fit has been drawn for the values of electricity demand rise by 564, 1182 and 1856 GWh over its base electricity demand of 27,522 GWh with every 1 °C, 2 °C and 3 °C increase in temperature in Delhi in 2015 generated by the global warming scenario presented in the study carried out by Gupta (2012).

By using the conversion factor of 0.82 kg CO_2/kWh, the increase in CO_2 emissions from electricity energy generation source have been computed from the increase in electricity demand as shown in Eq. (3).